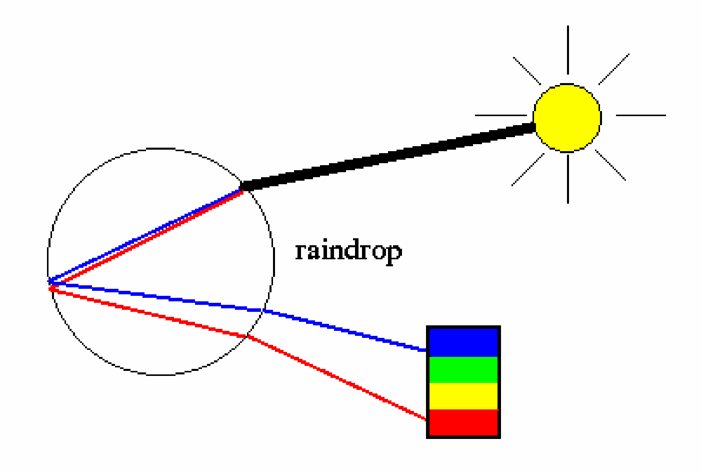
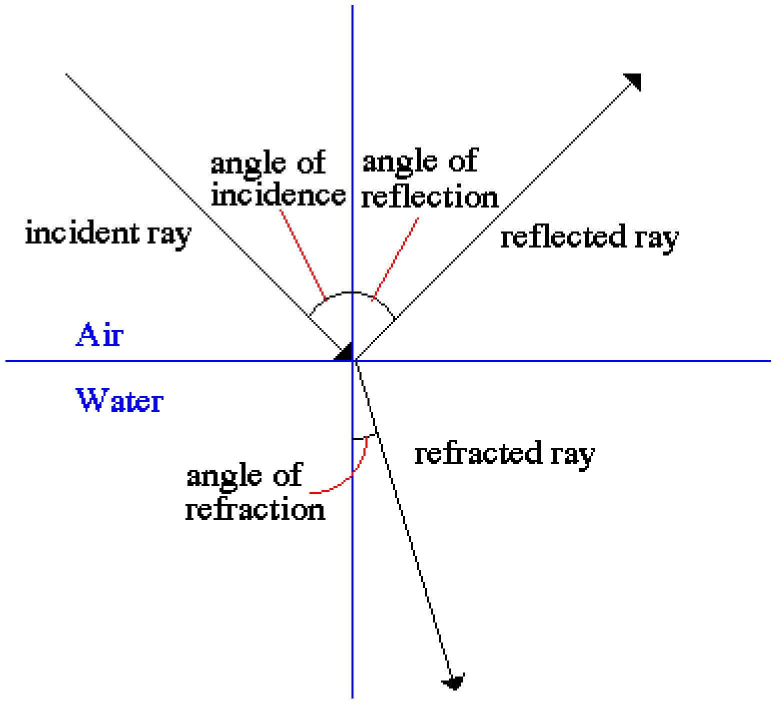
Waves

and

Light



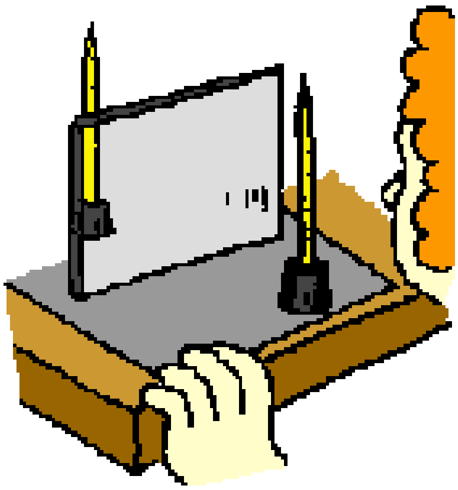


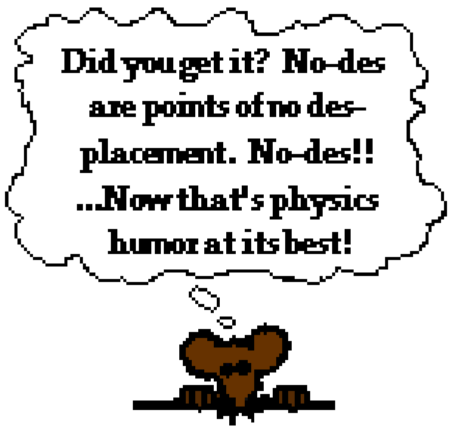
Waves and Light

Learning Outcomes:

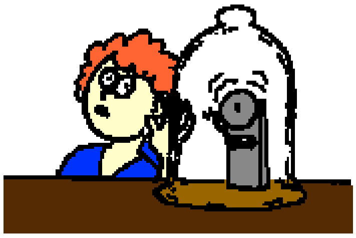
At the end of this unit students should be able to:

- Classify waves according to type of movement of particles (longitudinal/transverse) and describe a wave using wave parameters (speed, wavelength, period, frequency, amplitude).
- Illustrate changes in parameters and phase at a boundary between two media through reflection and refraction, including total internal reflection and the critical angle.
- Explain diffraction, superposition, interference and standing waves.
- Solve for an unknown quantity when a wave refracts.
- Use ray diagrams and formula to predict the position, size and orientation of images with mirrors and lenses.
- Recall the electromagnetic spectrum in order of wavelength and frequency and the properties of electromagnetic waves.



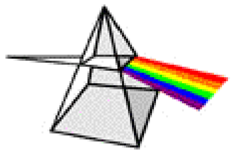


Content



The sound produced by the bell cannot be heard since sound cannot travel through a vacuum.

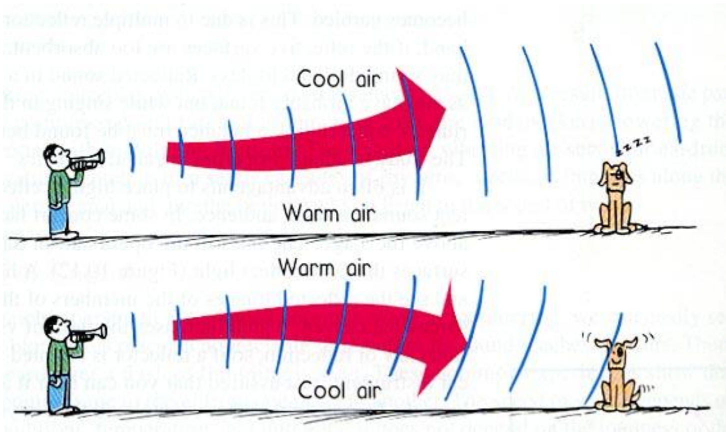
- Wave parameters (speed, wavelength, period, frequency, amplitude). $v = f\lambda$ $f = \frac{1}{T}$
- Wave properties: The phenomena of reflection, refraction, diffraction and interference as observed in water waves, light waves and sound waves.
- Dispersion.
- Superpositioning of two pulses going through each other.
- Constructive and Destructive Interference.
- Standing waves.
- Recognising nodes and antinodes.

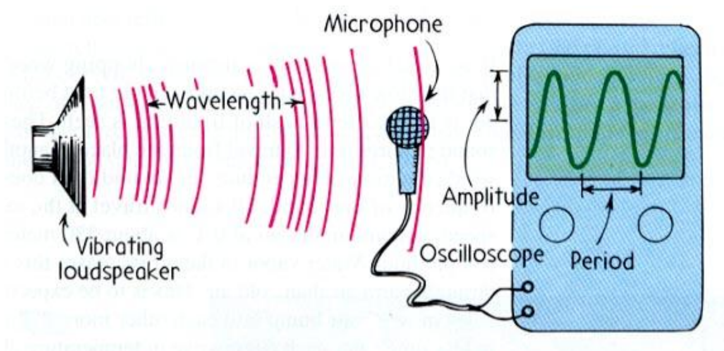


- Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$ $\frac{n_1}{n_2} = \frac{v_2}{v_1} = \frac{\lambda_2}{\lambda_1}$
- Definition of absolute refractive index.
- Total internal reflection.
- Mirrors and lenses: $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ $m = \frac{d_i}{d_o} = \frac{h_i}{h_o}$
- Focal point, pole, principal axis, focal length, magnification, real and virtual images, scale diagrams as a model of the situation, the determination of image distance/object distance by scale diagram and formula.
- Interference patterns for light, sound and water, practical examples.
- Electromagnetic Spectrum in order of wavelength or frequency.

Resources and Activities

- Videos: Intro to Waves; Refraction and images; Waves in the ocean.
- Ripple tank,
- Sound gear,
- Light gear,
- Ray diagram worksheets,
- Refraction worksheet,
- Interference worksheet,
- TIR practical





What are Waves?

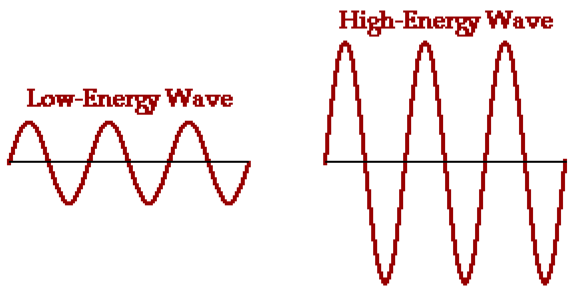
A wave is a disturbance, usually periodic, in a medium or a vacuum. Energy (kinetic) transfer by vibrations, no matter is moved.

Two types:

Mechanical Waves – require a medium to travel, e.g. Sound.

Electromagnetic (EM) Waves – don't require a medium, travel in a vacuum, e.g. Light

Definitions and Symbols



The amplitude of a wave is related to the energy which it transports.

$$E \propto A^2$$

Amplitude, A – Maximum displacement from the equilibrium, related to the amount of energy the wave has.

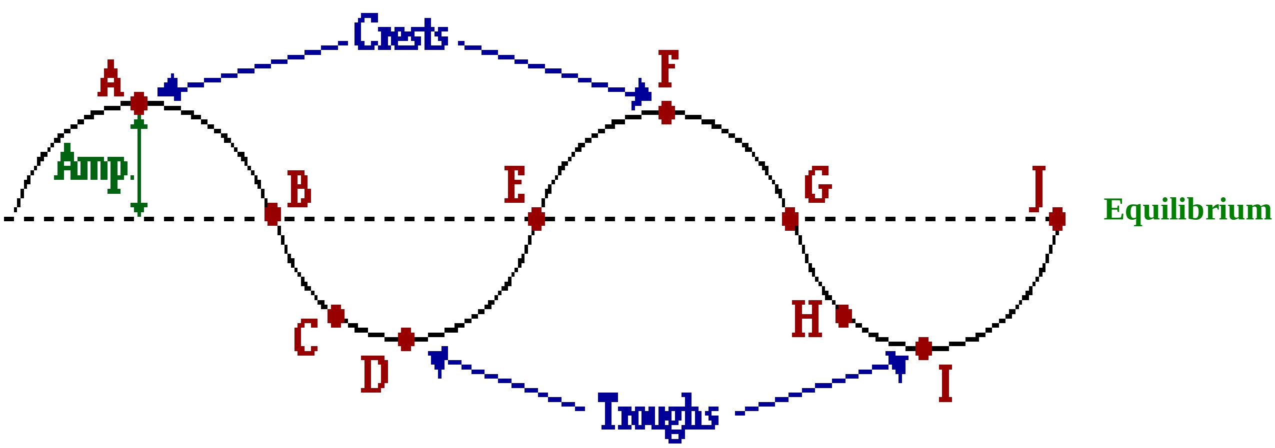
Wavelength, λ - length of one cycle.

Speed, *v* – how fast the wave is moving.

Period, T – time for one cycle to pass a point.

Frequency, *f* – number of cycles that pass a point in a second.

Equilibrium - undisturbed position of the medium.



Note:

$$T = \frac{1}{f} \quad \text{and} \quad v = f\lambda$$

Wavefronts - One way to show waves moving is to draw lines representing the same part of a wave, usually crests. These lines are called wavefronts and can be used to show how a wave is moving, by adding an arrow to indicate direction of travel. Wavefronts are at right angles to the direction of travel. This way of showing waves is generally used with water waves.

Rays - Another way of showing waves is to draw an arrow to indicate the direction the wave is travelling in. This depiction is generally used when light is being studied.

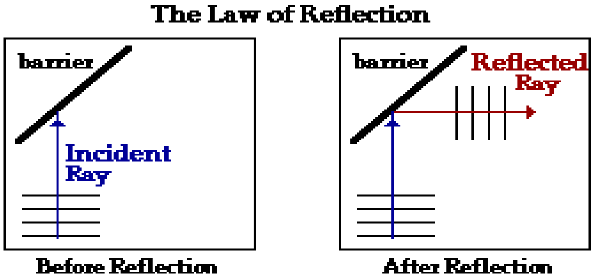
Phase – a term used to describe the relative motion of two waves of the same frequency, usually measured as an angle. 0° means the motion is exactly the same and is called 'in phase'. 180° means the motion is exactly opposite and is called 'out of phase'. Can also be used to describe points on the same wave.

***Speed** - It should be noted that wave speed is dependent upon properties of the medium the wave is in and independent of wave parameters. Even though the wave speed is calculated by multiplying wavelength by frequency, an alteration in wavelength does not affect wave speed. Rather, an alteration in wavelength affects the frequency in an inverse manner. A doubling of the wavelength results in a halving of the frequency; yet the wave speed is not changed.

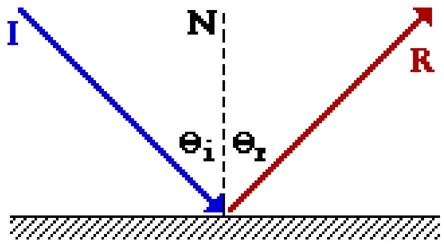
Properties of Waves

Reflection

– Reflection is the term used to describe what happens when a wave arrives at a barrier and changes direction.

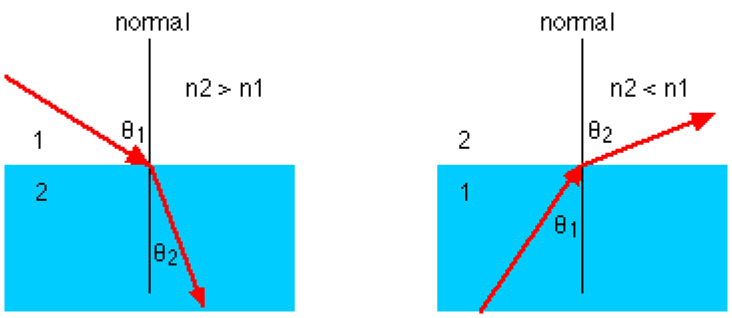


- For reflection of waves from a barrier the angle of reflection, θ_r is always equal to the angle of incidence, θ_i.



Refraction

- When a wave passes from one medium to another medium, it may change speed, wavelength and direction; frequency does not change. There may also be some reflection; note that whenever a wave passes through a boundary the wave may lose energy, usually to heat. The change in speed/wavelength and direction can be found from Snell's Law; note that the wave bends towards the normal when travelling to a denser media, and away from the normal when travelling to a less dense media. Refraction can also occur when the properties of the media change.

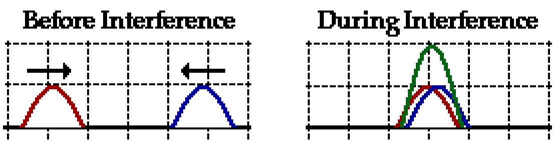


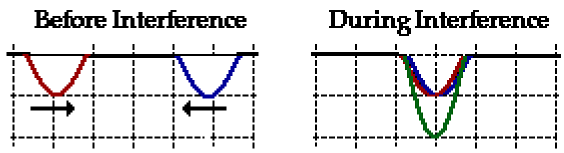
Snell's law : $n_1 \sin\theta_1 = n_2 \sin\theta_2$ or, equivalently, $\sin\theta_1 / \sin\theta_2 = v_1 / v_2$

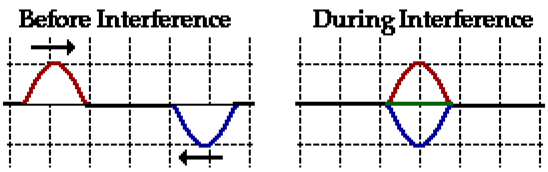
Interference

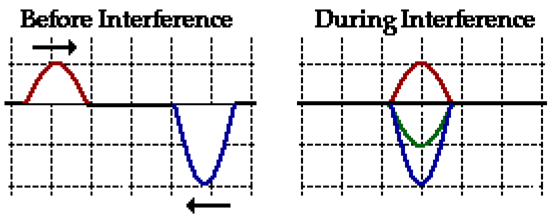
- When waves move through each other they superimpose or interfere with each other, either increasing or reducing displacement. This is called either constructive or destructive interference. Points where maximum displacement occurs are called anti-nodes and points where displacement is reduced to nothing, at the equilibrium, are called nodes.

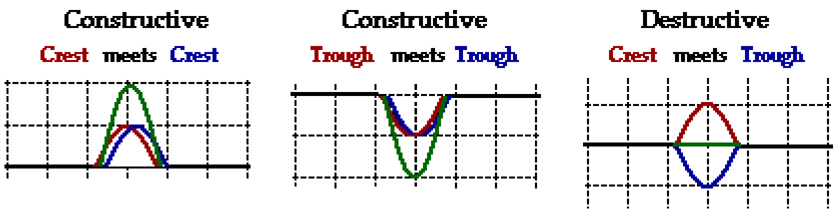
Note: nodes exhibit no movement and antinodes range from maximum displacement to no displacement to maximum…



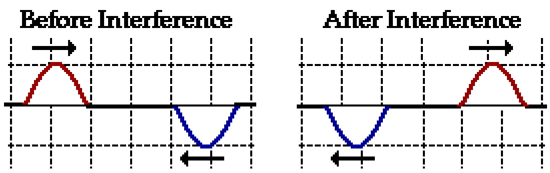








- After passing through each other the waves return to their original shape and continue in their original directions.

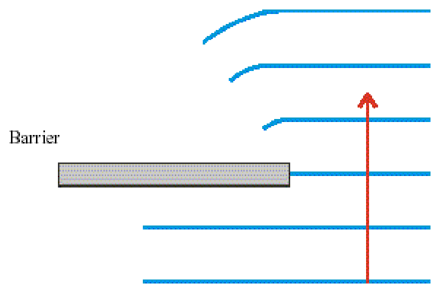


- Occasionally as waves pass through each other they may set up a repeating pattern or shape. This shape does not appear to move, rather just oscillate. This is called a standing wave, as opposed to a travelling wave. Standing waves form the basis of music.

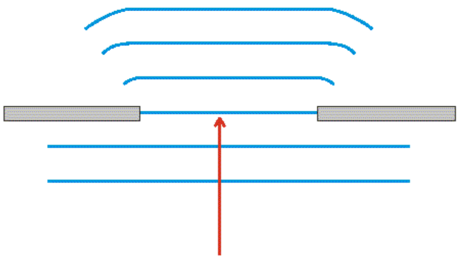
- More properly interference is about energy distribution as waves pass through each other.

Diffraction

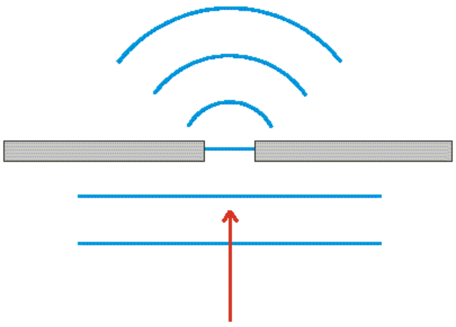
- Whenever a wave passes around a barrier or through a gap the wave spreads out past the obstruction. The amount of spreading depends on the wavelength of the wave and the size of the gap. In general large wavelengths diffract more and smaller gaps cause more diffraction.



Diffraction as plane waves pass the edge of a straight barrier



Diffraction as plane waves pass through an opening in a barrier



Diffraction varies directly with wavelength;
diffraction varies inversely with size of opening.

Types of Mechanical Wave Motion

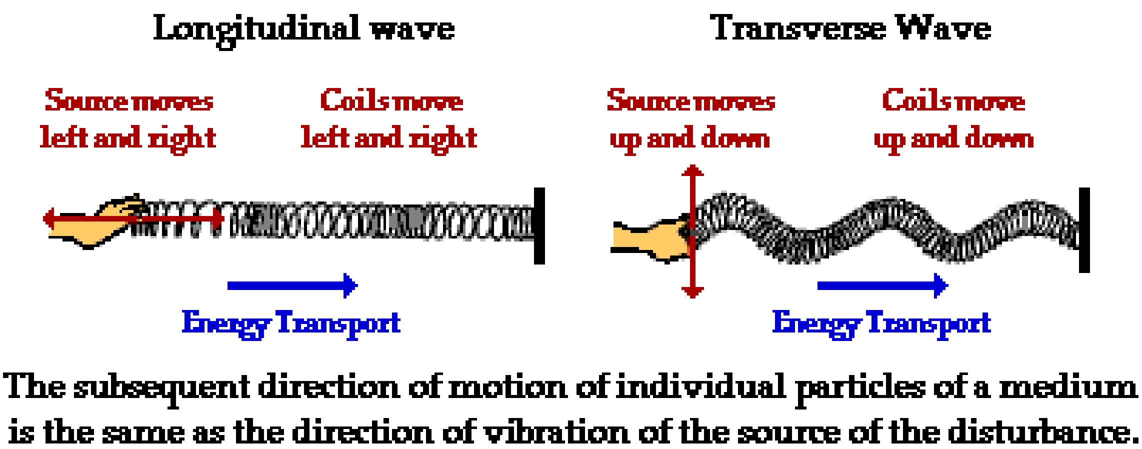
Longitudinal and Transverse waves

<u>TRANSVERSE WAVES</u>:

The vibration of the molecules is perpendicular to the direction the wave is travelling in.

<u>LONGITUDINAL WAVES</u>:

Vibration is parallel to the direction of motion.

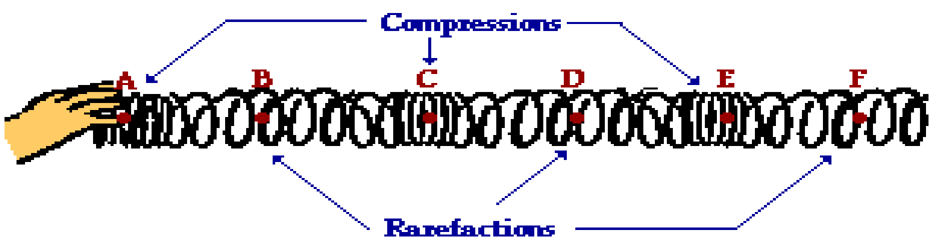


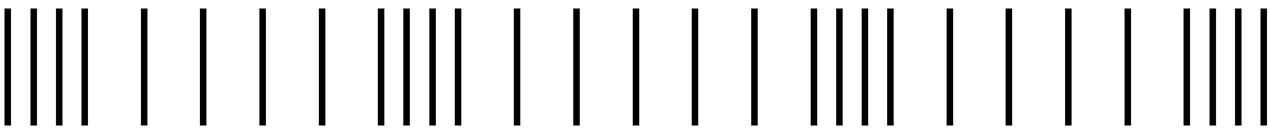
More about the two types of vibration

<u>Transverse</u>

Motion is not just up and down but side-to-side etc too.

<u>Longitudinal</u>





^Compression ^Rarefaction

<u>COMPRESSION</u>:

Molecules are compressed together

<u>RAREFACTION</u>:

Region of emptiness, molecules have moved as far apart as possible

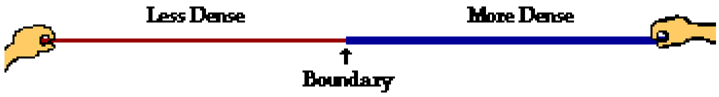
It is often much easier to view waves in transverse form. When viewed in transverse form the middle of a compression and the middle of a rarefaction correspond to the points of the wave at the equilibrium position. This is because in the middle of each there are molecules that have not moved from the equilibrium. The amount of compression/rarefaction indicates the amplitude of the wave.

Mechanical waves travelling through a solid medium can be either transverse waves or longitudinal waves. Yet waves travelling through the bulk of a fluid (a liquid or a gas) are always longitudinal waves. Transverse waves require a relatively rigid medium in order to transmit their energy. As one particle begins to move it must be able to exert a pull on its nearest neighbour. If the medium is not rigid, as is the case with fluids, the particles will slide past each other. This sliding action that is characteristic of liquids and gases prevents one particle from displacing its neighbour in a direction perpendicular to the energy transport. It is for this reason that only longitudinal waves are observed moving through the bulk of liquids such as our oceans.

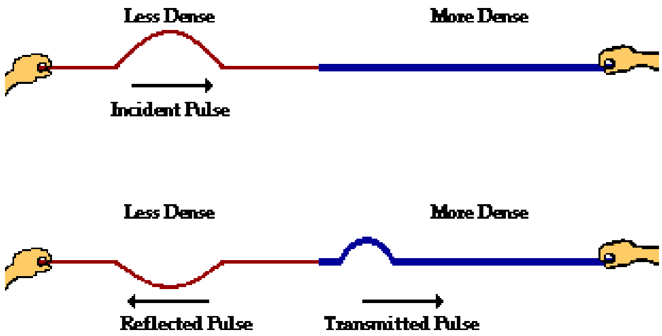
Reflection and Transmission of Pulses at a Boundary

When a wave, or pulse, passes from one medium to another some of the energy of the wave is transmitted to the new medium and some is reflected back into the original medium.

The more similar the media are, the greater the transmission of energy.

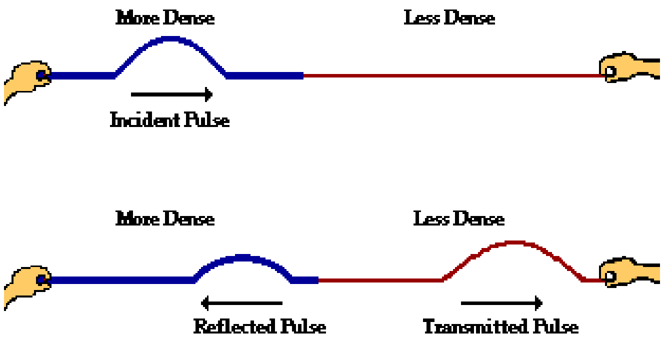


A wave traveling from a less dense to a more dense medium...



...will be reflected off the boundary and transmitted across the boundary into the new medium. The reflected pulse is inverted.

A wave traveling from a more dense to a less dense medium...

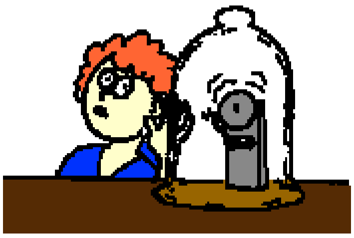


...will be reflected off the boundary and transmitted across the boundary into the new medium. There is no inversion.

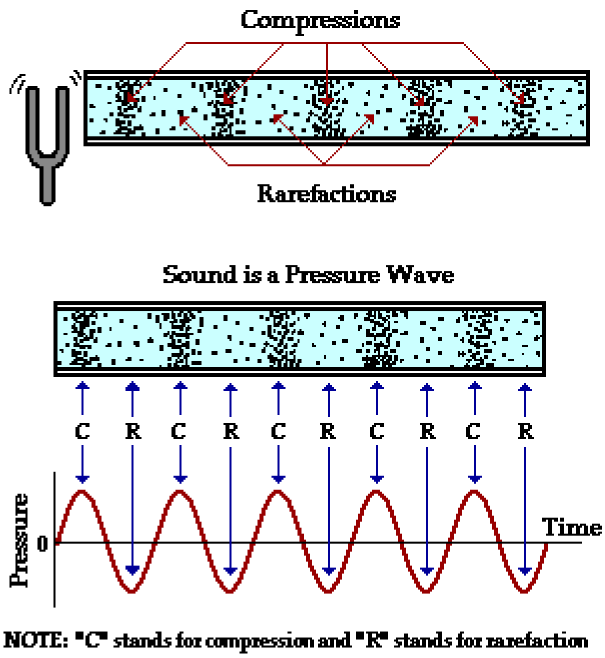
Examples of Waves

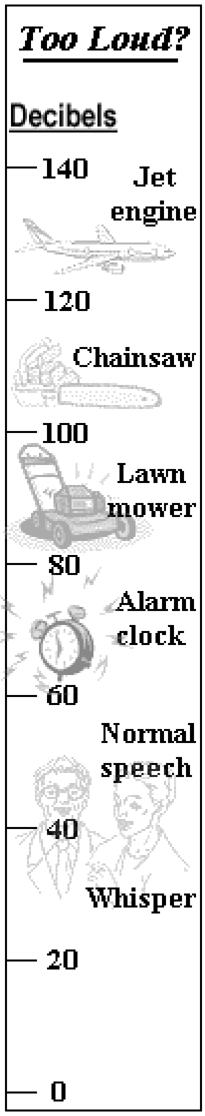
Sound

Sound travels as longitudinal vibrations of molecules in a medium.



The sound produced by the bell cannot be heard since sound cannot travel through a vacuum.





The speed of sound varies depending on the properties of the media through which it is travelling. Typically there are two essential types of properties which effect wave speed - inertial properties and elastic properties. Even though solids are denser than gases they have higher elastic properties.

Speed of Sound ($m\ s^{-1}$)	Medium
331.3	Air 0°C
1284	H_2 0°C
1498	Water 25°C
3500	Brass
5100	Aluminium

$$v_{solids} > v_{liquids} > v_{gases}$$

At normal atmospheric pressure, the temperature dependence of the speed of a sound wave through air is approximated by the following equation:

$$v = 331 \text{ m s}^{-1} + (0.6 \text{ m s}^{-1} \text{ C}^{-1})*T$$

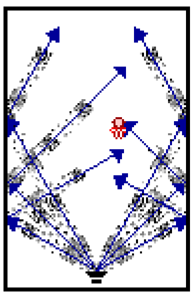
where:

v is the speed of the wave and

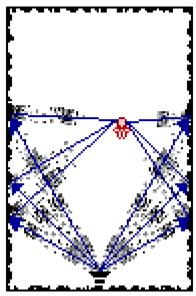
T is the temperature of the air in degrees Celsius.

Sound waves are produced over a very wide range of frequencies. Human beings can hear only a limited part of this range, approx 20 – 20, 000 Hz. Various frequencies have a variety of uses, especially ultrasound, frequencies above the threshold of Human hearing. Applications include: Echo sounding by bats, sonar, ultra sonic glasses, ultrasound imaging in medicine.

Reflection of sound waves off of surfaces can lead to one of two phenomenon - an **echo** or a **reverberation**. A reverberation often occurs in a small room with height, width, and length dimensions of approximately 17 meters or less. Why the magical 17 meters? The effect of a particular sound wave upon the brain endures for more than a tiny fraction of a second; the human brain keeps a sound in memory for up to 0.1 seconds. If a reflected sound wave reaches the ear within 0.1 seconds of the initial sound, then it seems to the person that the sound is *prolonged*. The reception of multiple reflections off of walls and ceilings within 0.1 seconds of each other causes reverberations - the prolonging of a sound. Since sound waves travel at about 340 m s^{-1} at room temperature, it will take approximately 0.1 s for a sound to travel the length of a 17 meter room and back, thus causing a reverberation. Reverberations can be observed when talking in an empty room, when honking the horn while driving through a highway tunnel or underpass, or when singing in the shower. In auditoriums and concert halls, reverberations occasionally occur and lead to the displeasing garbling of a sound.

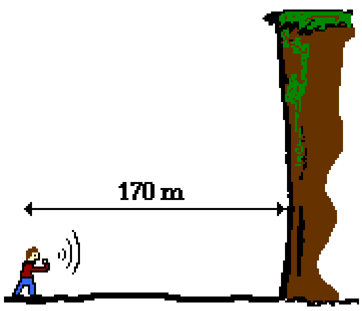


Smooth walls fail to give the room a feel of full sound.



Rough walls give a room a feel of full and lively sound.

But reflection of sound waves in auditoriums and concert halls do not always lead to displeasing results, especially if the reflections are *designed right*. Smooth walls have a tendency to direct sound waves in a specific direction. Subsequently the use of smooth walls in an auditorium will cause spectators to receive a large amount of sound from one location along the wall; there would be only one possible path by which sound waves could travel from the speakers to the listener. The auditorium would not seem to be as lively and full of sound. Rough walls tend to diffuse sound, reflecting it in a variety of directions. This allows a spectator to perceive sounds from every part of the room, making it seem lively and full. For this reason, auditorium and concert hall designers prefer construction materials that are rough rather than smooth.



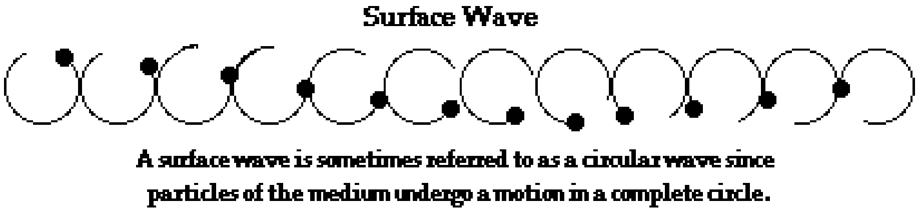
Reflection of sound waves also leads to echoes. Echoes are different than reverberations. Echoes occur when a reflected sound wave reaches the ear more than 0.1 seconds after the original sound wave was heard. If the elapsed time between the arrivals of the two sound waves is more than 0.1 seconds, then the sensation of the first sound will have *died out*. In this case, the arrival of the second sound wave will be perceived as a second sound rather than the prolonging of the first sound. There will be an echo instead of a reverberation.

Remember the sound for an echo has to travel there and back again.

The shape of the surface also effects reflection of sound waves off of surfaces. Flat or plane surfaces reflect sound waves in such a way that the angle at which the wave approaches the surface equals the angle at which the wave leaves the surface. Reflection of sound waves off of curved surfaces leads to a more interesting phenomenon. Curved surfaces with a parabolic shape have the habit of focusing sound waves to a point. Sound waves reflecting off of parabolic surfaces concentrate all their energy to a single point in space, the focal point; at that point, the sound is amplified. Parabolic-shaped satellite disks use this same principle of reflection to gather large amounts of electromagnetic waves and focus it at a point (where the receptor is located). Various animals make use of this effect. The Bull Moose utilizes his antlers as a satellite disk to gather and focus sound. Owls are equipped with spherically shaped facial disks, which can be manoeuvred in order to gather and reflect sound towards their ears.

The destructive interference of sound waves can also be used advantageously in **noise reduction systems**. Earphones have been produced which can be used by factory and construction workers to reduce the noise levels on their jobs. Such earphones capture sound from the environment and use computer technology to produce a second sound wave that is one-half cycle *out of phase*. The combination of these two sound waves within the headset will result in destructive interference and thus reduce a worker's exposure to loud noise.

Water

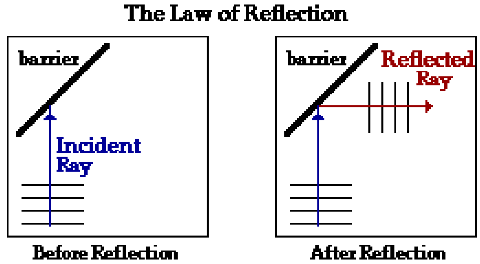


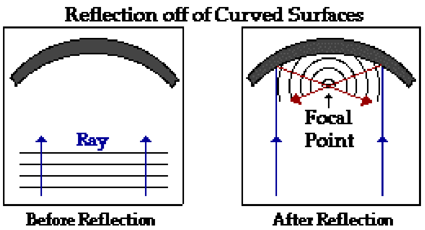
While waves that travel within the depths of the ocean are longitudinal waves, the waves that travel along the surface of the oceans are referred to as surface waves. A surface wave is a wave in which particles of the medium undergo a circular motion. Surface waves are neither longitudinal nor transverse. In longitudinal and transverse waves, all the particles in the entire bulk of the medium move in a parallel and a perpendicular direction (respectively) relative to the direction of energy transport. In a surface wave, it is only the particles at the surface of the medium that undergo the circular motion. The motion of particles tends to decrease as one proceeds further from the surface.

Most waves are caused by the action of the wind but some are generated by another means. Earthquakes can cause tsunamis, sometimes incorrectly called tidal waves. They have very long wavelengths, several hundred kilometres, and travel very quickly. In deep water they are only a few metres high but in shallow water they become much larger. As the waves approach shore they slow down and bunch up, eventually becoming a breaker when it can no longer draw in enough water to support itself.

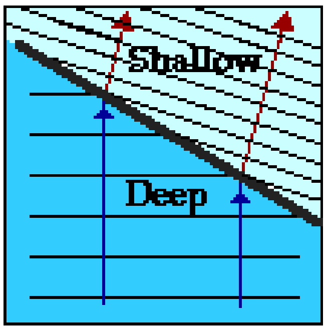
Water waves exhibit all of the properties of waves, that is, they reflect, refract, diffract and interfere.

Plane waves reflecting off a flat surface will remain planar but will become circular if reflected off curved surfaces. Circular waves may also remain the same or change shape depending on the shape of the surface.

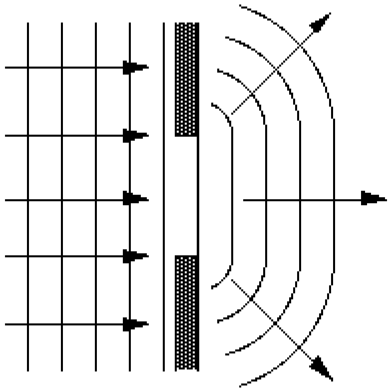




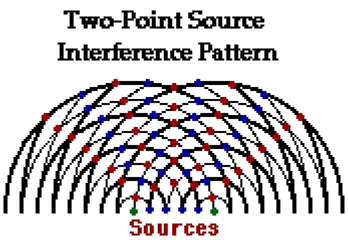
When the depth of water changes so does the speed of any waves in the water. Speed of waves in water is faster in deeper water

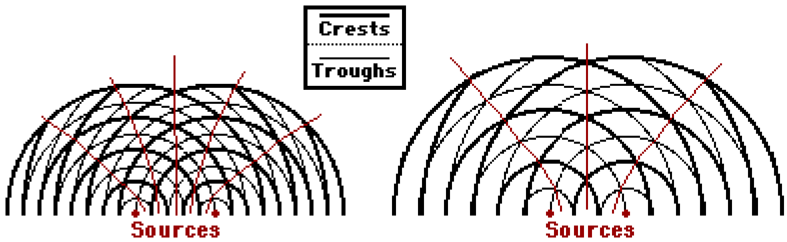


Water waves will pass through gaps and around barriers and then spread out; that is will be diffracted.



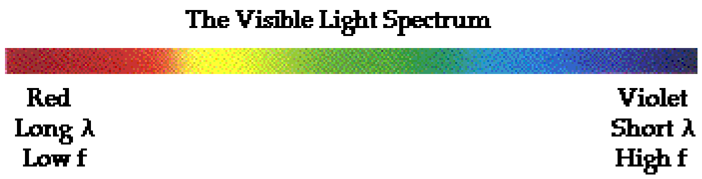
Water waves will form interference patterns.



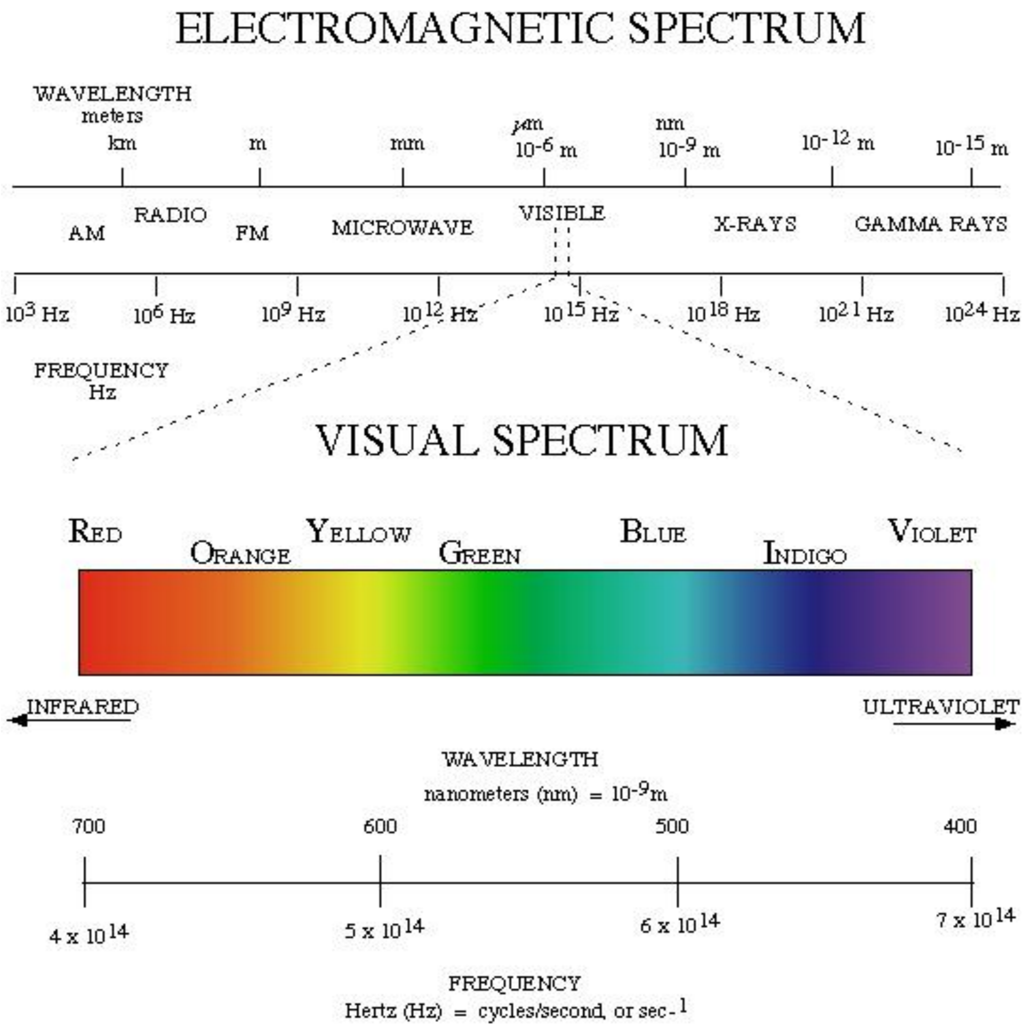


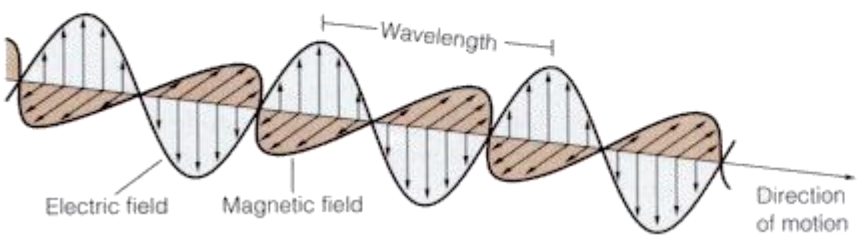
The proximity of the anti-nodal lines in a two-point source interference pattern is dependent upon the wavelength of the waves.

Light



Light usually travels in straight lines, this is sometimes called Rectilinear Propagation. Light is the visible part of a much larger group of waves. Collectively these waves are referred to as the Electromagnetic Spectrum. The Electromagnetic spectrum is waves that transfer energy in the form of oscillating magnetic and electric fields. Visible light is a very small part of the electromagnetic spectrum. Because it is fields that vibrate electromagnetic waves can travel through a vacuum.





The Duality of Light

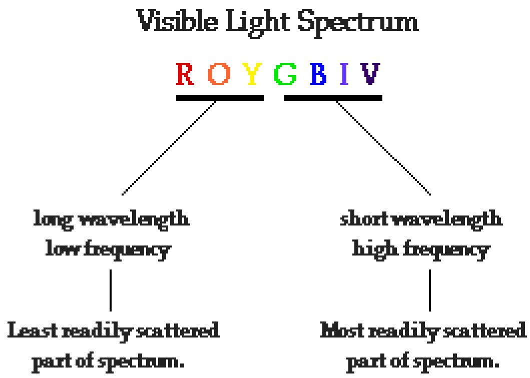
The nature of light, whether it was a particle or a wave, raged for nearly 2500 years. At different times the different models gained ascendancy and were accepted as 'right'. Da Vinci argued for a wave model, Newton for a particle model. Huygens also argued for a wave model for light. In each case there was evidence to support that particular model. Because of his prestige Newton's particle model became the accepted model during the 18 century. Basically the particle model explains the following observations about light.

Travels in straight lines (shadows demonstrate this).
Obeys the inverse square law (double distance and brightness reduces by a factor of four).
Can cross a vacuum (doesn't need a medium).
Obeys the laws of reflection.
Exerts a pressure on things it hits.
Bends under the influence of gravity.
Heats substances that absorb it.

The particle model cannot explain interference and relies on the speed of light increasing when entering optically denser media.

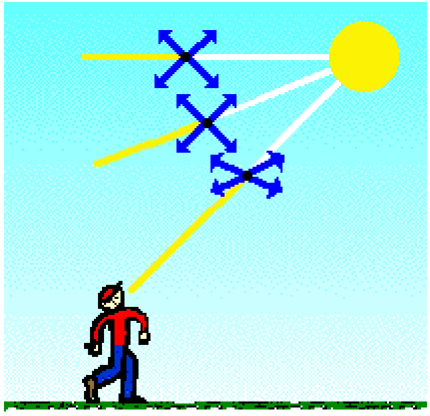
Early in the nineteenth century experiments by Young showed that light could cause interference patterns. Later that century Foucault showed that the speed of light slows down in optically denser media. The particle model was under sentence of death. However a new phenomenon discovered at the end of the nineteenth century, the photoelectric effect, could not be explained unless light was a particle. De Broglie settled the debate early last century, he suggested that light could behave as a particle and as a wave; this is called wave-particle duality and is vital to the branch of Physics known as Quantum Mechanics. Generally when convenient we treat light as a wave and when convenient light is treated as a particle. The particles of light are called photons.

Blue Skies and Red Sunsets

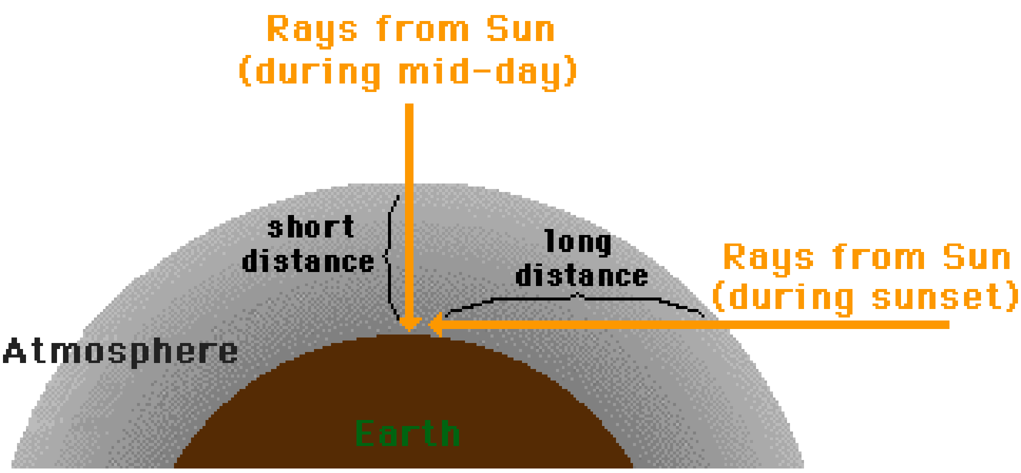


The sun emits light waves with a range of frequencies. Some of these frequencies fall within the visible light spectrum and thus are detectable by the human eye. Since sunlight consists of light with the range of visible light frequencies, it appears white. This white light is incident towards Earth and illuminates both our outdoor world and the atmosphere that surrounds our planet. As we sight at various objects in our surroundings, the colour that we perceive is dependent upon the colour(s) of light that are reflected or transmitted by those objects to our eyes. So as we view a green leaf on a tree outdoors, the atoms of the chlorophyll molecules in the leaf are absorbing most of the frequencies of visible light (except for green) and reflecting the green light to our eyes; the leaf thus appears green. And as we view the black asphalt street, the atoms of the asphalt are absorbing all the frequencies of visible light and no colour is reflected to our eyes; the asphalt street thus appears black (the absence of colour). In this manner, the interaction of sunlight with matter contributes to the colour appearance of our surrounding world. The interaction of sunlight with matter can result in one of three wave behaviours: absorption, transmission, and reflection. The atmosphere is a gaseous sea, which contains a variety of types of particles; the two most common types of matter present in the atmosphere are gaseous nitrogen and oxygen. These particles are most effective in scattering the higher frequency and shorter wavelength portions of the visible light spectrum. This scattering process involves the

absorption of a light wave by an atom followed by reemission of a light wave in a variety of directions. The amount of multidirectional scattering that occurs is dependent upon the frequency of the light (in fact, it varies according to f^4). Atmospheric nitrogen and oxygen scatter violet light most easily, followed by blue light, green light, etc. So as white light (ROYGBIV) from the sun passes through our atmosphere, the high frequencies (BIV) become scattered by atmospheric particles while the lower frequencies (ROY) are most likely to pass through the atmosphere without a significant alteration in their direction. This scattering of the higher frequencies of light illuminates the skies with light on the BIV end of the visible spectrum. Compared to blue light, violet light is most easily scattered by atmospheric particles; however, our eyes are more sensitive to light with blue frequencies. Thus, we view the skies as being blue in colour.


The yellow appearance of the noon-day sun is due to the scattering of the higher frequencies of sunlight.

Meanwhile, the light that is not scattered is able to pass through our atmosphere and reach our eyes in a rather non-interrupted path. The lower frequencies of sunlight (ROY) tend to reach our eyes as we sight directly at the sun during midday. While sunlight consists of the entire range of frequencies of visible light, not all frequencies are equally intense. In fact, sunlight tends to be most rich with yellow light frequencies. For these reasons, the sun appears yellow during midday due to the direct passage of dominant amounts of yellow frequencies through our atmosphere and to our eyes. The appearance of the sun changes with the time of day. While it may be yellow during midday, it gradually turns colour as it approaches sunset. This can be explained by light scattering. As the sun approaches the horizon line, sunlight must traverse a greater distance through our atmosphere. As the path which sunlight takes through our atmosphere increases in length, ROYGBIV encounters more and more atmospheric particles. This results in the scattering of greater and greater amounts of yellow light. During sunset hours, the light passing through our atmosphere to our eyes tends to be most concentrated with red and orange frequencies of light. For this reason, the sunsets have a reddish-orange hue. The effect of a red sunset becomes more pronounced if the atmosphere contains more and more particles. The presence of sulfur aerosols (emitted as an industrial pollutant) in our atmosphere contributes to some magnificent sunsets (and some very serious environmental problems).

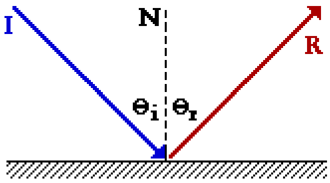


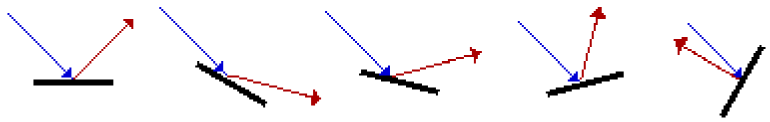
Reflection of Light

We see object either because they emit light (luminous) or reflect light (nonluminous or illuminated). There are two forms of reflection Diffuse and Regular (specular).

Regular Reflection

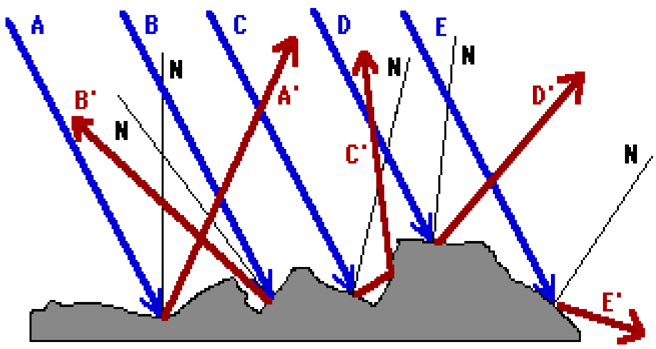
Reflection off of smooth surfaces such as mirrors or a calm body of water leads to a type of reflection known as specular reflection. It this form of reflection it is easy to see $\theta_i = \theta_r$. The orientation of the surface doesn't matter.



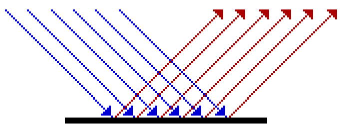


Diffuse Reflection

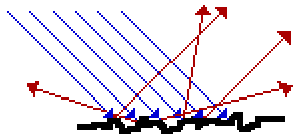
Reflection off of rough surfaces such as clothing, paper, and the asphalt roadway leads to a type of reflection known as diffuse reflection. The law of reflection $\theta_i = \theta_r$ still holds for each individual ray follows the law of reflection. However, the roughness of the material means that each individual ray meets a surface that has a different orientation. Subsequently, when the individual rays reflect according to the law of reflection, they scatter in different directions



Whether the surface is microscopically rough or smooth has a tremendous impact upon the subsequent reflection of a beam of light.

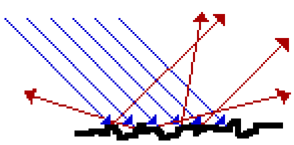


Specular Reflection
(smooth surfaces)

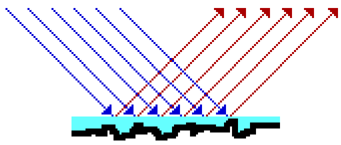


Diffuse Reflection
(rough surfaces)

There are several interesting applications of this distinction between specular and diffuse reflection. One application pertains to the relative difficulty of night driving on a dry asphalt roadway compared to a wet asphalt roadway. Most drivers are aware of the fact that driving at night on a wet roadway results in an annoying glare from oncoming headlights. The glare is the result of the specular reflection of the beam of light from an oncoming car. Normally a roadway would cause diffuse reflection due to its rough surface. But if the surface is rough, water can fill in the crevices and smooth out the surface. Rays of light from the beam of an oncoming car hit this smooth surface, undergo specular reflection and remain concentrated in a beam. The driver perceives an annoying glare caused by this concentrated beam of reflected light.



A dry asphalt roadway diffuses incident light.



When wet, water fills in the crevices, resulting in specular reflection and a glare.

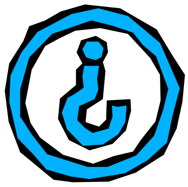
Nature of Images

When an image is formed in a mirror it has certain characteristics, these characteristics are called the nature of an image.

An image is either Inverted or Upright, this discibes the orientation of the image with repect to the object the image is formed from.

Object

Upright or Erect image



Inverted image

An object can be Magnified or Diminished, sometimes the image can also be the same size as the object.

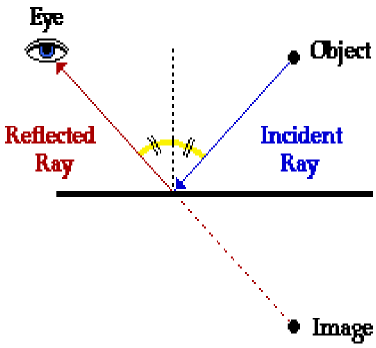
Object

Magnified or Enlarged image

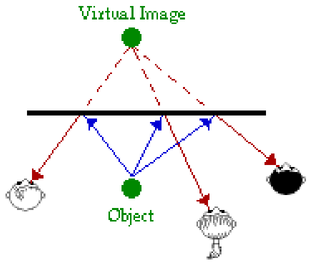
Diminished image

An image can also be Real or Virtual. A real image is one that can be projected or placed onto a screen. The light rays actually pass through the point where the image is. A virtual image cannot be projected onto a screen. The image is formed by the mind backtracking rays to place the image; no actual light rays pass through the point where the image is. Images formed by plane mirrors are virtual images.

Images in Plane Mirrors



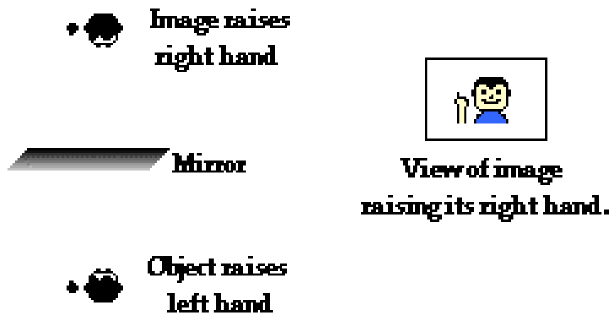
When we look into a plane (flat) mirror the image we see appears to be behind the mirror. This is because the brain is not capable of determining that the light ray carrying the image has changed direction. The brain 'knows' that light travels in straight lines so when it tries to place an object it backtracks along the observed ray to place the image. For multiple observers this remains true so all people looking in a mirror would 'see' the image in the same place.



All observers would perceive light to be diverging from the same point - the image point.

Also when we see an image in a plane mirror the image has been Laterally Inverted, or left-right swapped.

Left-right Image Reversal



Right Angle Mirrors

A right angle mirror is a pair of plane mirrors adjoined at right angles to each other. In such a set up a third image is formed, this image is not laterally inverted. This is because it is formed from the reflection of light ray off both mirrors so it has been left-right swapped twice.

The Three Images of a Right Angle Mirror

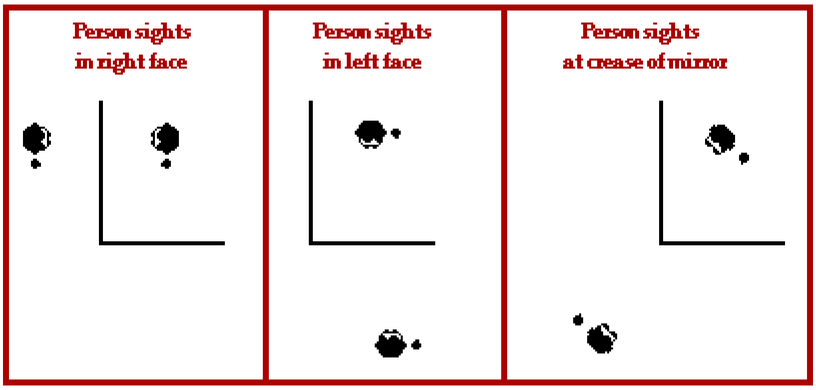
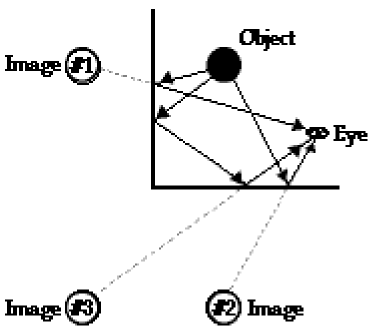
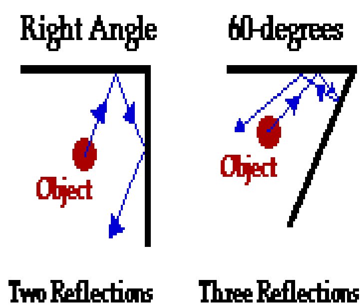
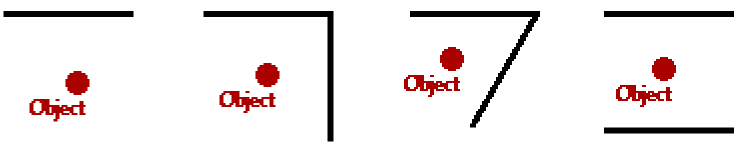


Diagram A Diagram B Diagram C



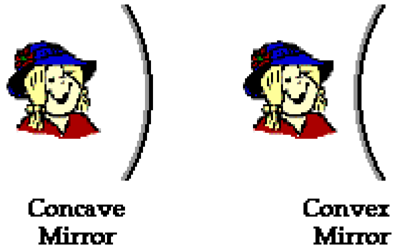
It is possible to increse the number of images seen by reducing the angle between the mirrors. This increases the number of reflections of each mirror. Some images will be laterally inverted and some will not. Those with an even number of reflections will not be laterally inverted. Eventually for two mirror held opposite to each other there will be an infinite number of images seen.





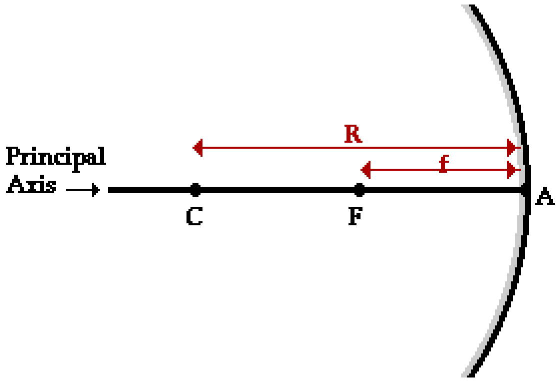
A single mirror produces 1 image. Two mirrors at 90° produce 3 images. Two mirrors at 60° produce > 3 images. Two mirrors at 0° produce infinite images.

Images in Curved Mirrors



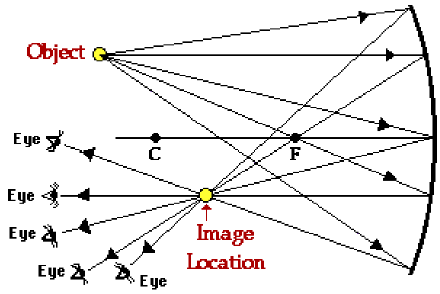
Curved mirrors come in two forms concave mirrors and convex nirrors. Concave mirrors reflect on the inside of the curev and are sometimes called converging mirrors. Convex mirrors reflect from the outside of the curve and are sometimes called diverging mirrors.

Concave mirrors



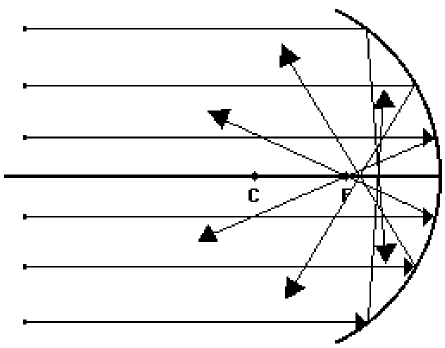
Points of interest on a concave mirror:

C Centre of curvature
F Focal point, or principal focus
A Pole
R Radius of curviture
f Focal length, f is also half the distance of R



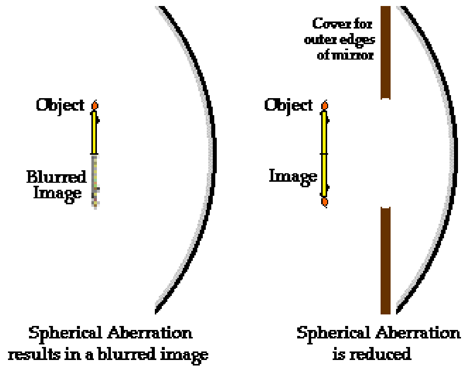
The reason that concave mirrors are called converging mirrors is that any ray that is parallel to the principal axis will be reflected through the focal point.

Spherical Aberration



Spherical mirrors have an aberration. There is an intrinsic defect with any mirror that takes on the shape of a sphere; this defect prohibits the mirror from focusing light to a precise point. The defect is most noticeable for light striking the outer edges of the mirror. Rays which strike the outer edges of the mirror fail to focus in the same precise location as light rays which strike the inner portions of the mirror. While light striking the interior of a mirror may focus to a point, any light striking the edges fails to focus at that same point. The result is that the images of objects as seen in spherical mirrors are often blurry.

This problem is not limited to light that is incident upon the mirror and travelling parallel to the principal axis. Any incident ray that strikes the outer edges of the mirror is subject to this effect.



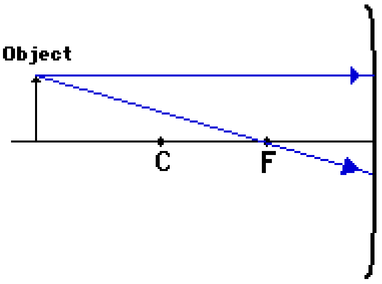
Spherical aberration is most commonly corrected by use of a mirror with a different shape. Usually, a parabolic mirror is substituted for a spherical mirror. The outer edges of a parabolic mirror have a significantly different shape than that of a spherical mirror. Parabolic mirrors create sharp, clear images that lack the blurriness that is common to spherical mirrors.

Ray diagrams for concave mirrors

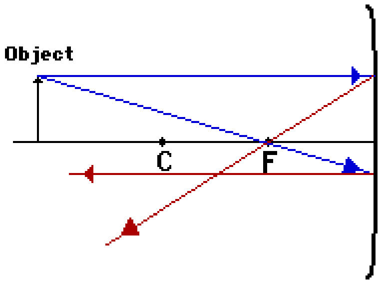
When trying to determine the nature of an image it is often to draw scale diagrams, such diagrams are called ray diagrams. They can be used for all mirror and lenses, and each case has its own specific rules, which are generally the same.

1. Draw the principal axis, the position of the mirror (usually to simplify things this is drawn as a straight line), mirror symbol, and the focal point. Place the object on the diagram (usually this is drawn as some simple object such as an arrow or tree)

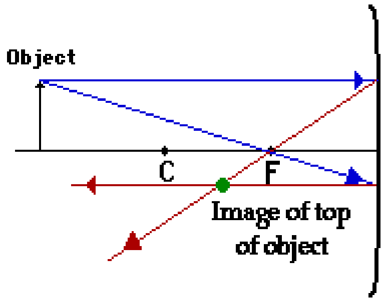
2. From the top of the object and draw two incident rays travelling towards the mirror. Using a ruler accurately draw one ray so that it passes exactly through the focal point on the way to the mirror. Draw the second ray such that it travels exactly parallel to the principal axis. Place arrowheads upon the rays to indicate their direction of travel.



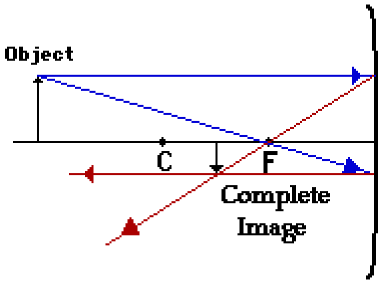
3. The ray that passes through the focal point on the way to the mirror will reflect and travel parallel to the principal axis. Use a ruler to accurately draw its path. The ray that travelled parallel to the principal axis on the way to the mirror will reflect and travel through the focal point. Use a ruler to accurately draw its path. Place arrowheads upon the rays to indicate their direction of travel. Extend the rays past their point of intersection.



4. The image point of the top of the object is the point where the two reflected rays intersect. Mark the image of the top of the object. If your were to draw a third pair of incident and reflected rays, then the third reflected ray would also pass through this point. This is merely the point where all light from the top of the object would intersect upon reflecting off the mirror. Of course, the rest of the object has an image as well and it can be found by applying the same steps to another chosen point. To simplify things the rest of the image is drawn to the principal axis.

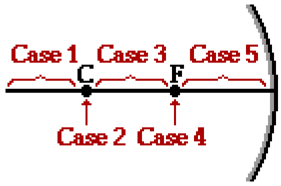


Sometimes a third ray might be needed to locate the position of the image. In that case a ray passing through the centre of curvature can be used. A ray passing through the centre of curvature will be reflected back through itself.



Unfortunately a concave mirror produces a number of different images depending on where the object is placed.

There are five such cases.



Case 1: The object is located *beyond* C

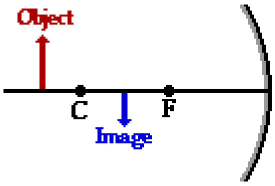


Image is real, inverted and diminished

Case 2: The object is located at C

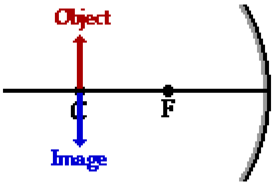
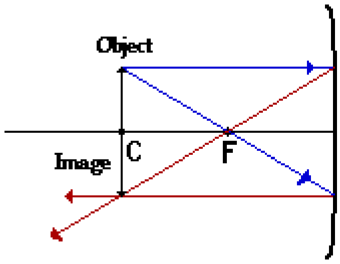
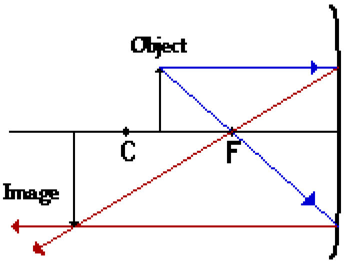


Image is real and inverted



Ray Diagram for Object Located at C



Ray Diagram for Object Located Between C and F

Case 3: The object is located between C and F

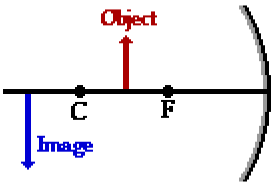
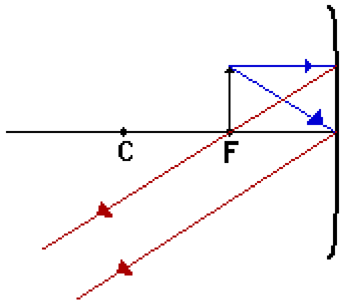
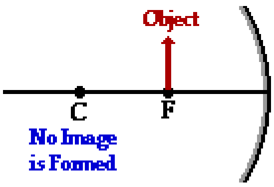


Image is real, inverted and magnified

Case 4: The object is located at F



Ray Diagram for Object Located at F
(an image is not formed)



No image

Case 5: The object is located *in front of* F

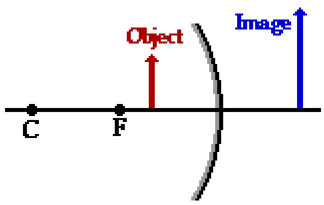
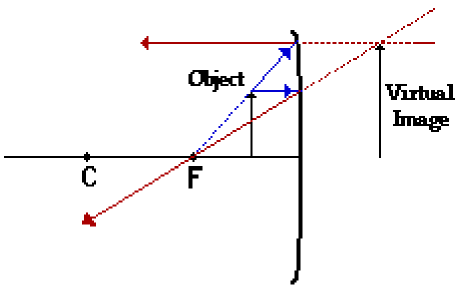
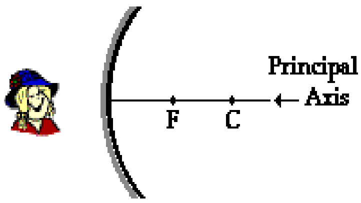


Image is virtual, upright and magnified



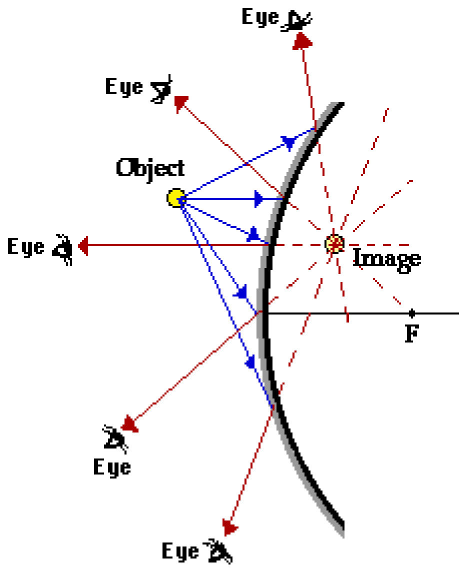
Ray Diagram for Object Located in Front of F

Convex Mirrors



A Convex Mirror with its Negative Focal Length

The points of interest for a convex mirror are the same as those for a concave mirror except the focal point and centre of curvature are on the other side of the mirror to the object, this is sometimes referred to as having a negative focal length.

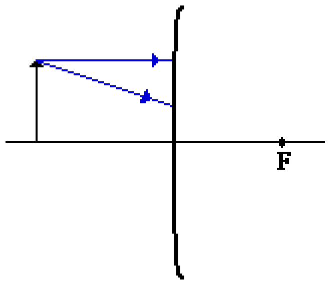


The convex mirror is sometimes called a diverging mirror. This is because the reflected rays all appear to diverge, or spread out, from the same point.

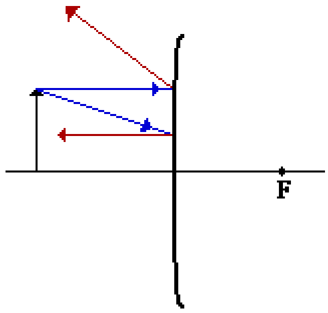
Ray diagrams for convex mirrors

The rules for a convex mirror's ray diagram are very similar to the rules for a ray diagram for a concave mirror.

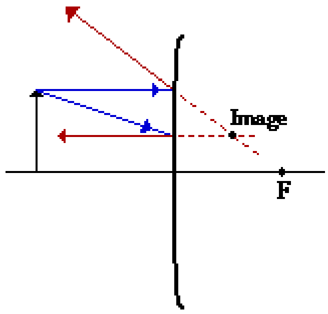
1. Draw the principal axis, the position of the mirror (usually to simplify things this is drawn as a straight line), mirror symbol, and the focal point. Place the object on the diagram (usually this is drawn as some simple object such as an arrow or tree)



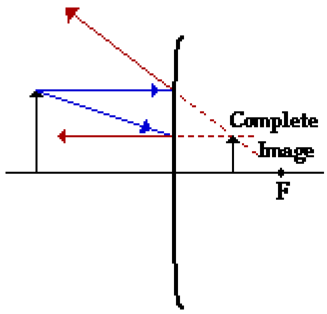
2. From the top of the object and draw two incident rays travelling towards the mirror. Using a ruler accurately draw one ray so that it would pass exactly through the focal point if it passed through the mirror. Draw the second ray such that it travels exactly parallel to the principal axis. Place arrowheads upon the rays to indicate their direction of travel.



3. The ray that would have passed through the focal point will reflect and travel parallel to the principal axis. Use a ruler to accurately draw its path. The ray that travelled parallel to the principal axis on the way to the mirror will reflect and travel as though it came from the focal point. Use a ruler to accurately draw its path. Place arrowheads upon the rays to indicate their direction of travel. Extend the rays past their point of intersection.

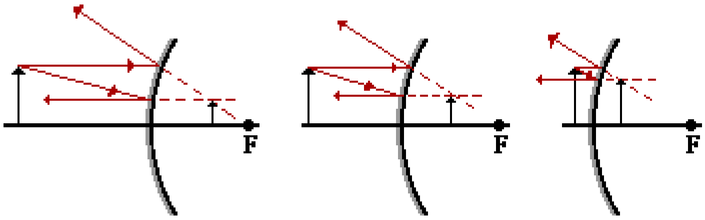


4. The image point of the top of the object is the point where the two reflected rays intersect. Mark the image of the top of the object. If your were to draw a third pair of incident and reflected rays, then the third reflected ray would also pass through this point. This is merely the point where all light from the top of the object would intersect upon reflecting off the mirror. Of course, the rest of the object has an image as well and it can be found by applying the same steps to another chosen point. To simplify things the rest of the image is drawn to the principal axis.

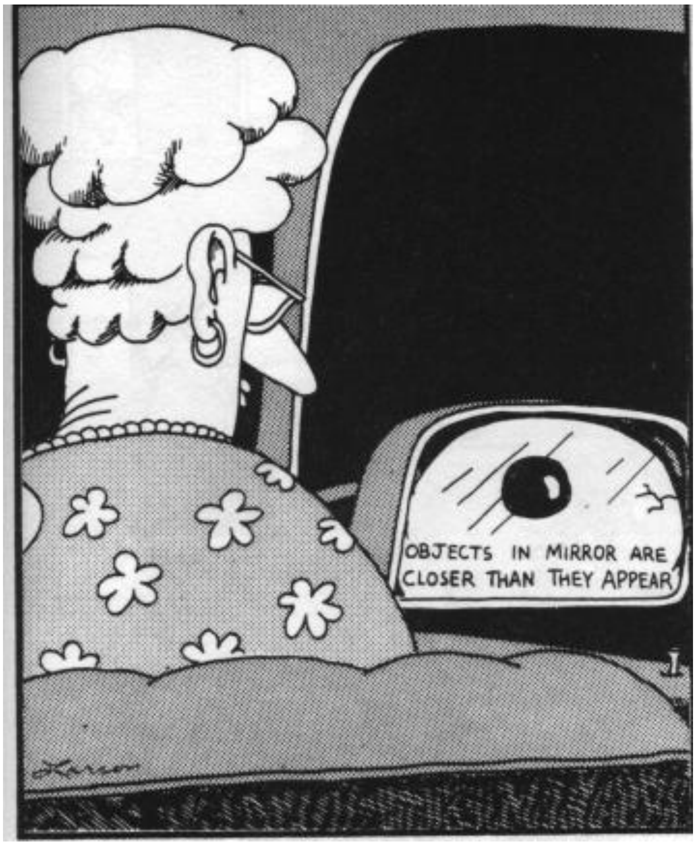


Again sometimes a third ray might be needed to locate the position of the image. In that case a ray is drawn as if it would have passed through the centre of curvature can be used. A ray that would pass through the centre of curvature will be reflected back through itself.

With a convex mirror only one type of image is ever generated. All images are virtual, upright and diminished.



Convex mirrors are used when an image is required and an enlarged viewing area is desirable. They are used for security purposes in shops. Some intersections and parking buildings use convex mirrors to improve traffic safety. The drawback of the convex mirror in these situations is that they make the image appear smaller. This can lead to problems judging distances. In cars rear vision mirrors are convex. Any image seen in them is smaller than the object and therefore appears further away than it really is.



Calculating the image from formula

As well as drawing ray diagram in order to find out the nature of an image it is possible to calculate certain aspects of an image. There are two sets of formulae that can be used.

Newton

$$s_i s_o = f^2 \quad \text{and} \quad m = \frac{f}{s_o} = \frac{s_i}{f}$$

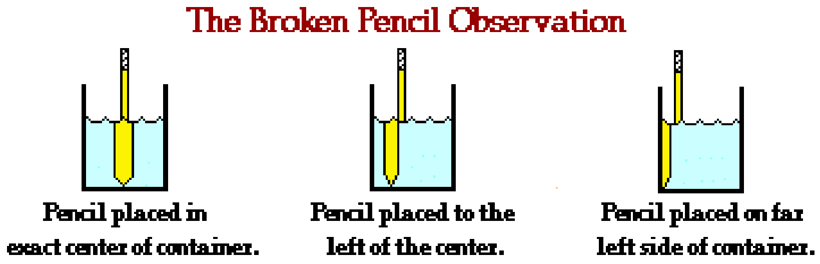
Descartes

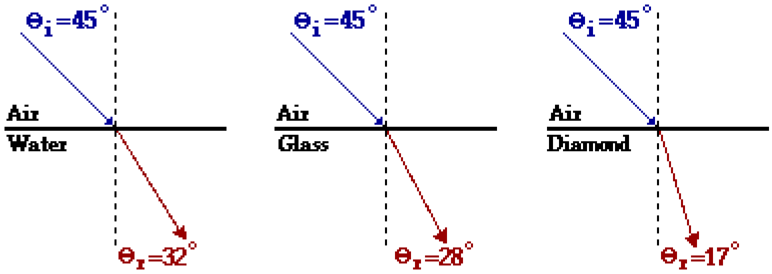
$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \quad \text{and} \quad m = \frac{d_i}{d_o} = \frac{h_i}{h_o}$$

where

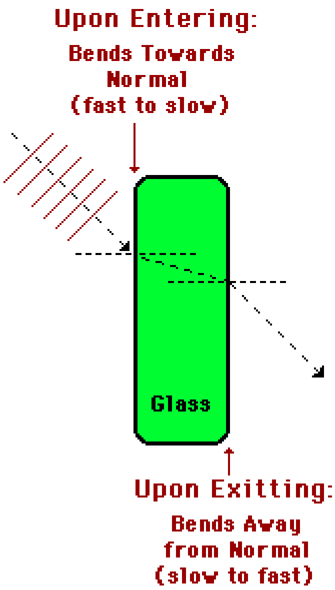
Refraction of Light

When a ray of light passes from one medium to another medium, it may change direction as it enters the new medium, when this happens its speed and wavelength also change. There may also be some reflection. Like reflection the angles of incidence and reflection are measured from the normal. The amount of refraction that occurs depends on the media on either side of the boundary, not all rays of light will be refracted by the same amount, even if the angle of incidence is the same. Refraction can also occur when the properties of the media change; this can lead to such things as mirages. Note that a wave that has been refracted does not change its frequency.





Refraction occurs because the speed of a wave is different in different media, as the wave crosses the boundary part of it slows down or speeds up, depending on the media involved.

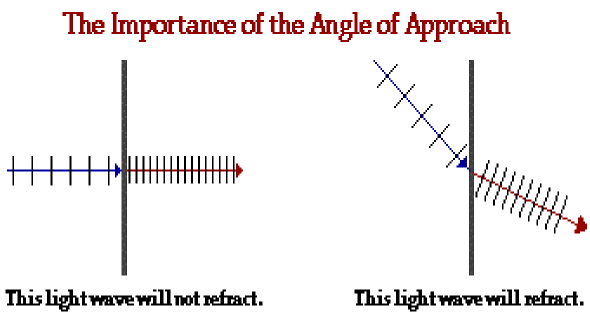


Light Travelling from a Fast to a Slow Medium

If a ray of light passes across the boundary from a material in which it travels fast into a material in which travels slower, then the light ray will bend towards the normal line.

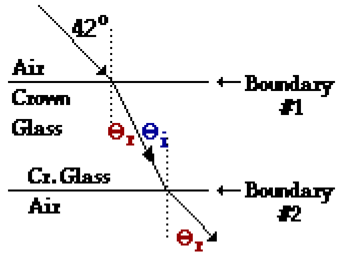
Light Travelling from a Slow to a Fast Medium

If a ray of light passes across the boundary from a material in which it travels slowly into a material in which travels faster, then the light ray will bend away from the normal line.



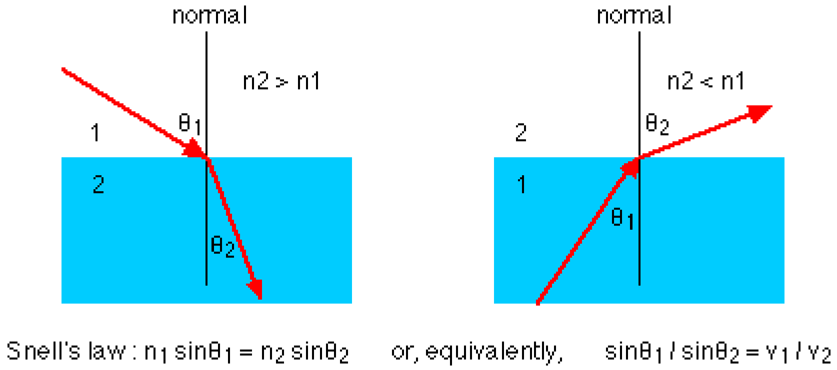
The angle that the ray hits the boundary at is very important to the amount of refraction observed. If the ray enters the new medium at an angle of incidence of 0° then there will be no observed change of direction, the speed and wavelength will still change however.

If a wave that has been refracted then leaves the new medium and returns to the original medium through a boundary parallel to the first it will resume travelling in its original direction, only shifted slightly off its original path



Snell’s Law

Snell’s Law is a mathematical formula that links the angles of incidence and refraction to the change in speed and change in wavelength observed when a wave refracts.



$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \frac{n_1}{n_2} = \frac{v_2}{v_1} = \frac{\lambda_2}{\lambda_1}$$

where n is the respective refractive indices of the media involved, θ is the respective angle between the ray and the normal in each media, v is the respective speeds of the wave/ray in each media and λ is the respective wavelengths of the wave in each media.

n is called the index of refraction and is a constant that is characteristic of a particular substance. It is the ratio of the speed of light in a vacuum to the speed of light in that substance, and so has no units.

$$n = \frac{c}{v}$$

where n is the index of refraction, c is the speed of light in a vacuum, and v is the speed of light in the medium.

Material	**Index of Refraction**	
Vacuum	1.0000	<--lowest optical density
Air	1.0003	
Ice	1.31	
Water	1.333	
Ethyl Alcohol	1.36	
Plexiglas	1.51	
Crown Glass	1.52	
Light Flint Glass	1.58	
Dense Flint Glass	1.66	
Zircon	1.923	
Diamond	2.417	
Gallium phosphide	3.50	<--highest optical density

Examples

1. A ray of light is incident on a boundary between air and water. The ray is travelling from the air to the water. Given that the refractive index of air is 1.00 and the refractive index of water is 1.33, if the angle of incidence is 45° what will be the angle of refraction?

Given:

$\theta_{air} = 45°$

$n_{air} = 1.00$

$n_{water} = 1.33$ and $n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\theta_{water} = ???$

$$\Rightarrow \quad n_{air} \sin\theta_{air} = n_{water} \sin\theta_{water}$$

$$1.00 \times \sin 45 = 1.33 \times \sin\theta_{water}$$

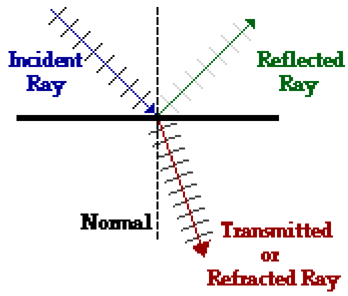
$$\frac{1.00 \times 0.707}{1.33} = \sin\theta_{water}$$

$\theta_{water} = 32.1°$

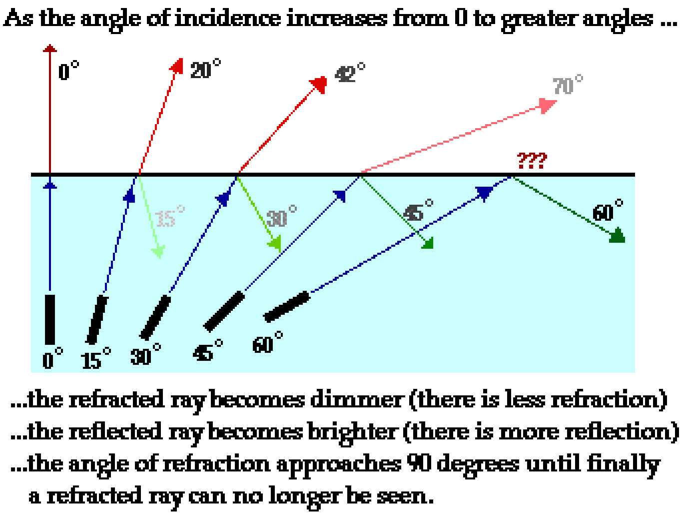
2. One of the ways to tell fake diamonds from real ones is that the refractive indices of the two materials, diamond and cubic zirconium, are different, and so light will travel differently through the two media. Given that the refractive index of diamond is 2.42 and the refractive index of cubic zirconium is 2.17

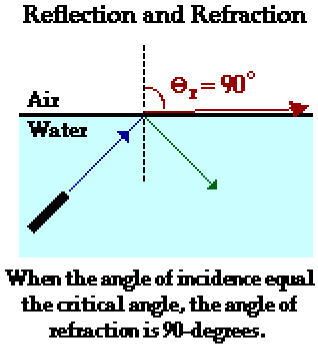
Features of the Refraction of Light

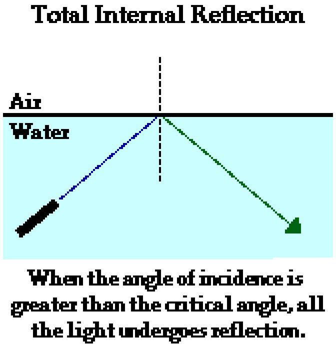
Total Internal Reflection



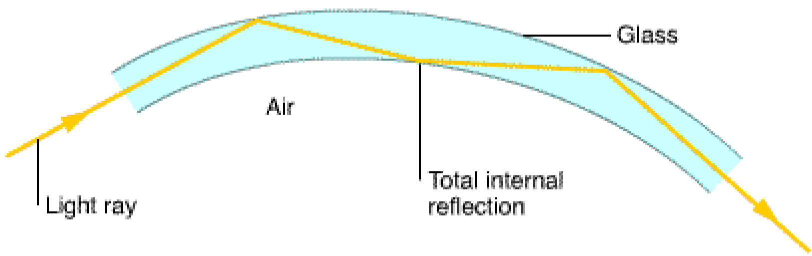
When light passes through a boundary not all of the light is refracted, some of the light is reflected back into the original medium. As the angle of incidence increases the amount of light reflected also increases. If the material is travelling from an optically denser medium to a less dense one the angle of refraction will be greater than the angle of incidence. As the angle of incidence gets larger the angle of refraction will get even larger. Eventually the angle of refraction will be 90, the angle of incidence at this point is called the critical angle and at this point an interesting phenomenon occurs. The light beam is now only reflected; no light leaves the original medium. This is called Total Internal Reflection.





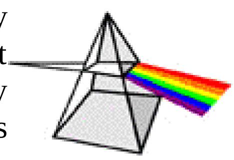


This phenomenon is very useful to us. Fibre Optic Cables rely on TIR to convey information with very little loss of signal. The cable weighs less than conventional copper wire and does need as many repeater stations along its length. However the fibre optic cable is harder to join and is easier to break than conventional wires.



Dispersion

When white light is refracted by a prism the component colours may become spread out and form a spectrum, this occurs because each colour of light has a different wavelength and hence all the colours are refracted slightly differently. This same affect causes rainbows. With dispersion red light is refracted least and blue/violet light the most.



Apparent Depth

When light ray travels from the bottom of a stream or pond it is refracted as it leaves the water. The result is that the body of water appears shallower than it really is.

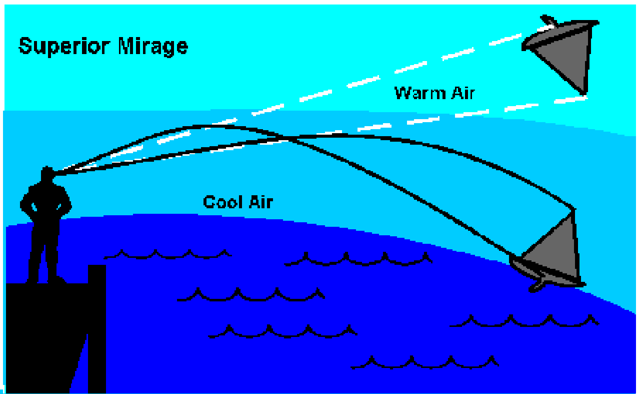
Parallel Displacement

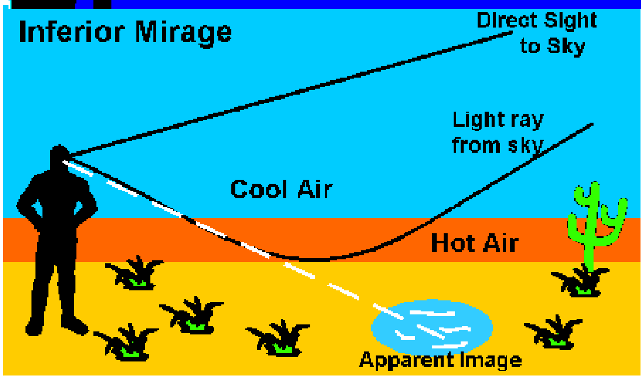
When a light ray passes through a medium that has parallel boundaries and re-enters its original medium, such as a glass window, it is travelling in the original direction but has been shifted over a certain distance.

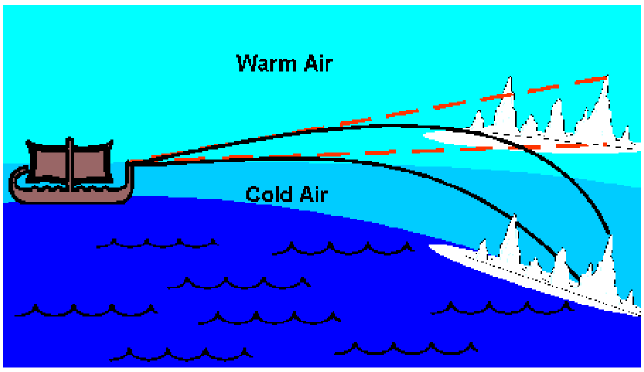
Mirages

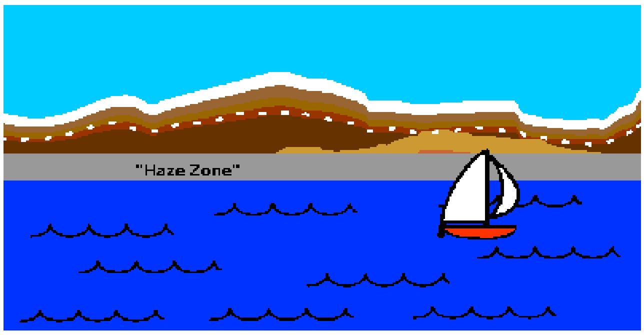
A mirage is an illusion that is cause by rays of light. When light rays travel through the air they encounter air of different temperatures, and densities. As they travel through these different air layers the rays can be refracted in different ways. When the rays reach the eye the image they form can become a mirage. What is seen depends on whether the immediate layer above the Earth's surface is a hot or cold layer.

The most common mirages seem to form bodies of water in the ground that aren't really there. They are in fact another 'picture' of the sky. The brain just interprets the image that it sees as one formed by a body of water.



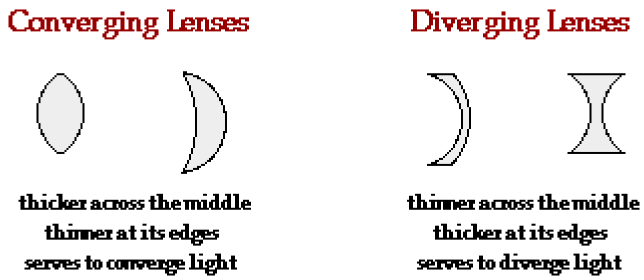




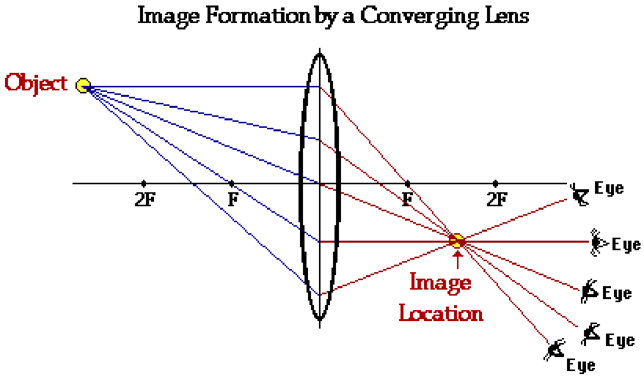


Lenses

When light passes through a curved transparent substance, it is refracted. If a piece of glass or other transparent material takes on the appropriate shape, it will be capable of taking rays of incident light and either converging them to a point or appear to diverge them from a point. Such a piece of glass is referred to as a lens.

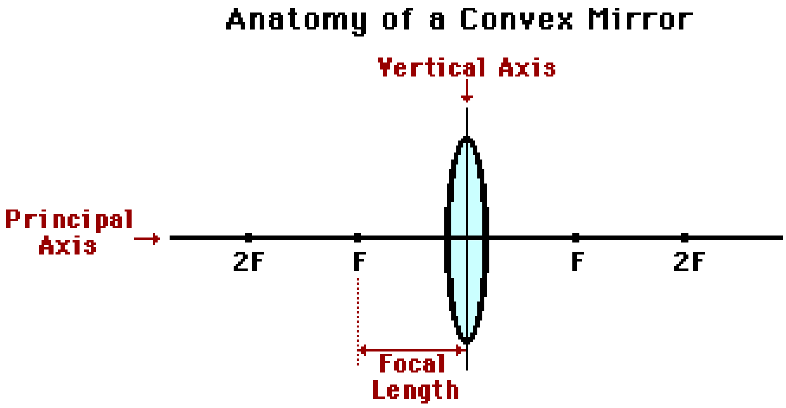


A lens that has both surfaces convex is called a bi-convex lens, but this is often shortened to just **convex lens**. A convex lens is a converging lens. A lens that has both surfaces concave is called a bi-concave lens, again this is often shortened to just **concave lens**. A concave lens is a diverging lens. These two types of lenses - convex and concave lenses will be the only types of lenses that will be discussed in this course in detail. Other lenses include: plano-convex, plano-concave, converging meniscus and diverging meniscus.



Convex lenses

Points of interest on a convex lens:



Ray Diagrams for convex lenses

There are three refraction rules for a converging lens

- Any incident ray traveling parallel to the principal axis of a converging lens will refract through the lens and travel through the focal point on the opposite side of the lens.
- Any incident ray traveling through the focal point on the way to the lens will refract through the lens and travel parallel to the principal axis.
- An incident ray that passes through the center of the lens will in effect continue in the same direction that it had when it entered the lens.

How to draw a ray diagram for a concave lens

1. Draw the principal axis, the position of the lens (vertical axis), the lens symbol and the two focal points.

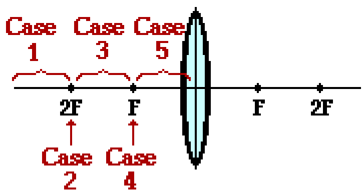
2. Pick a point on the top of the object and draw three incident rays traveling towards the lens. Using a ruler accurately draw one ray so that it passes exactly through the focal point on the way to the lens. Draw the second ray such that it travels exactly parallel to the principal axis. Draw the third incident ray such that it travels directly to the exact center of the lens. Place arrowheads upon the rays to indicate their direction of travel.
3. The ray that passes through the focal point on the way to the lens will refract and travel parallel to the principal axis. The ray that traveled parallel to the principal axis on the way to the lens will refract and travel through the focal point. And the ray that traveled to the exact center of the lens will continue in the same direction. Use a ruler to accurately draw these paths. Place arrowheads upon the rays to indicate their direction of travel. Extend the rays past their point of intersection

4. Mark the image of the top of the object. The image point of the top of the object is the point where the three refracted rays intersect. All three rays should intersect at exactly the same point. This point is merely the point where all light from the top of the object would intersect upon refracting through the lens. Of course, the rest of the object has an image as well and it can be found by applying the same three steps to another chosen point. To simplify things the rest of the image is drawn to the principal axis.

There are a number of different images formed depending on where the object is placed; like a concave mirror

There are five such cases.

Case 1: The object is located *beyond* C



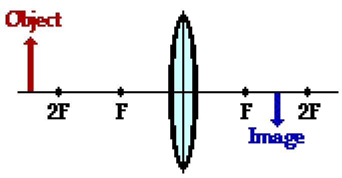


Image is real, inverted and diminished

Case 2: The object is located at C

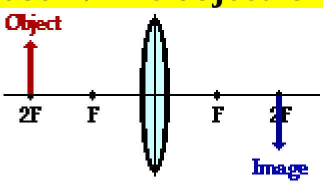
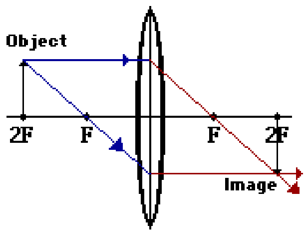
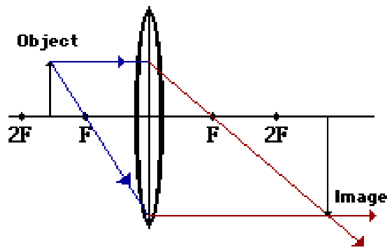


Image is real, inverted



Ray Diagram for Object Located at 2F



Ray Diagram for Object Located Between F and 2F

Case 3: The object is located between C and F

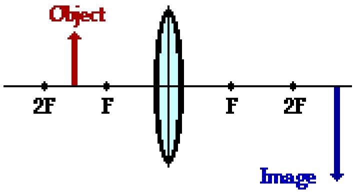
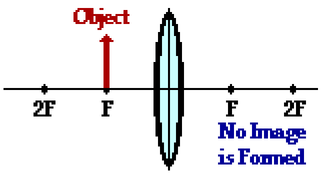
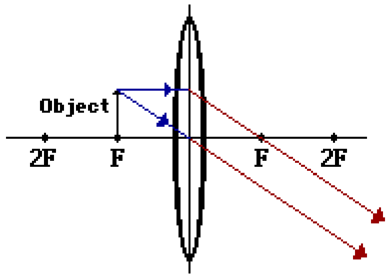


Image is real, inverted and magnified

Case 4: The object is located at F



No image



Ray Diagram for Object Located at F
(an image is not formed)

Case 5: The object is located *in front of* F

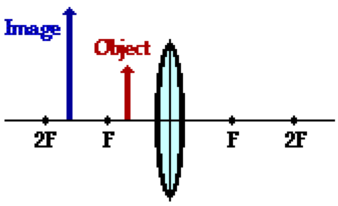
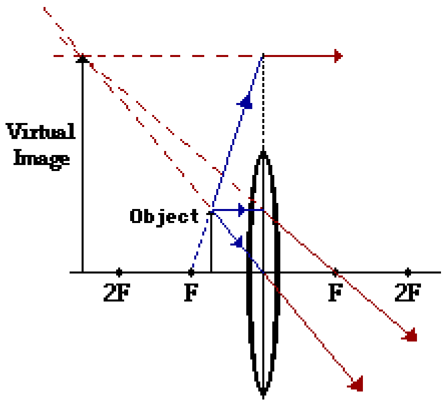


Image is virtual, upright and magnified



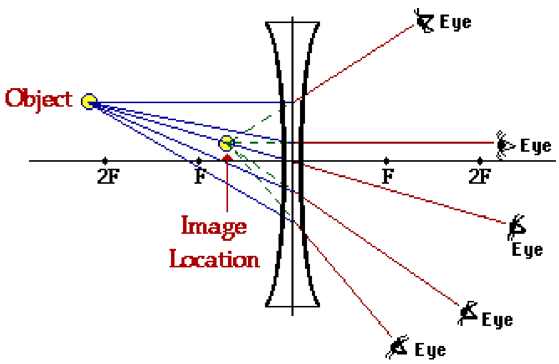
Ray Diagram for Object Located in Front of F

Concave lenses

The concave lens has the same layout as a convex lens.

Ray Diagram for concave lenses

Image Formation by a Diverging Lens



There are also three Refraction Rules for a Diverging Lens.

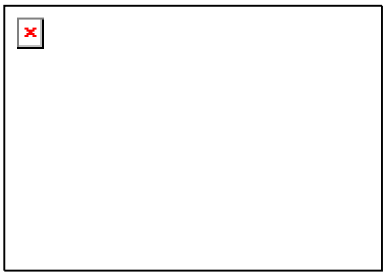
- Any incident ray traveling parallel to the principal axis of a diverging lens will refract through the lens and travel *as though it came from the focal point.*
- Any incident ray traveling towards the focal point on the way to the lens will refract through the lens and travel parallel to the principal axis.
- An incident ray that passes through the center of the lens will in effect continue in the same direction that it had when it entered the lens.

The method of drawing ray diagrams for a concave lens

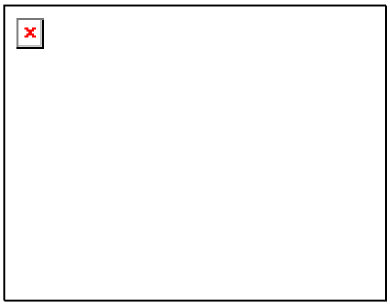
.

1. Draw the principal axis, the position of the lens (vertical axis), the lens symbol and the two focal points

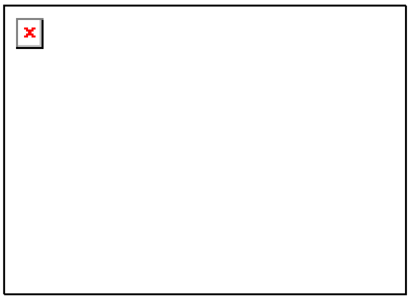
2. Pick a point on the top of the object and draw three incident rays traveling towards the lens. Using a ruler accurately draw one ray so that it travels towards the focal point on the opposite side of the lens; this ray will strike the lens before reaching the focal point; stop the ray at the point of incidence with the lens. Draw the second ray such that it travels exactly parallel to the principal axis. Draw the third ray to the exact center of the lens. Place arrowheads upon the rays to indicate their direction of travel.

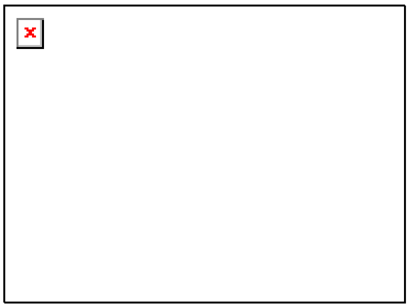


3. The ray that travels towards the focal point will refract through the lens and travel parallel to the principal axis. The ray that traveled parallel to the principal axis on the way to the lens will refract and travel in a direction such that it appears to have come from the focal point. The ray that traveled to the exact center of the lens will continue to travel in the same direction. Use a ruler to accurately draw these paths. Place arrowheads upon the rays to indicate their direction of travel. The three rays should be diverging upon refraction.

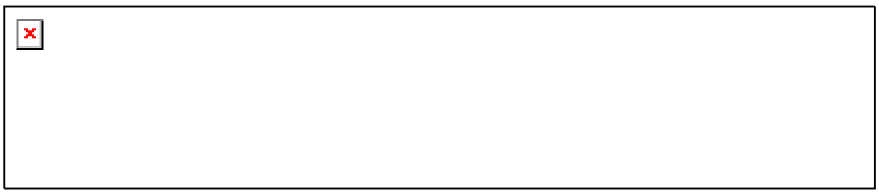


4. The image point of the top of the object is the point where the three refracted rays intersect. Since the three refracted rays are diverging, they must be extended behind the lens in order to intersect. Using a ruler extend each of the rays using dashed lines. Draw the extensions until they intersect. All three extensions should intersect in the same location. The point of intersection is the image point of the top of the object. The three refracted rays would appear to diverge from this point. This is merely the point where all light from the top of the object would appears to diverge from after refracting through the concave lens. Of course, the rest of the object has an image as well and it can be found by applying the same three steps to another chosen point. To simplify things the rest of the image is drawn to the principal axis.



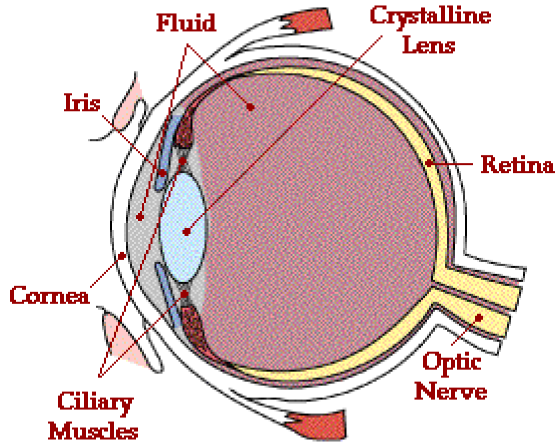


With a concave lens only one type of image is ever generated. All images are virtual, upright and diminished

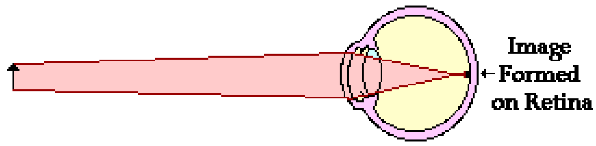


Uses of Lenses

The Eye

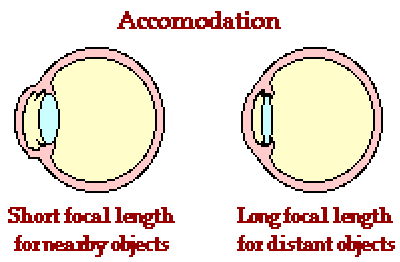


The eye is our window to the world. Without it we would have much less information on the world around us. The eye has evolved to focus rays of light from objects onto a series of light sensitive cells. These cells then send electrical signals to the brain, which deciphers them and we 'see' an object. Because the place that the image is formed on does not move in order to focus the shape of the lens has to alter in order to view objects at different distances.



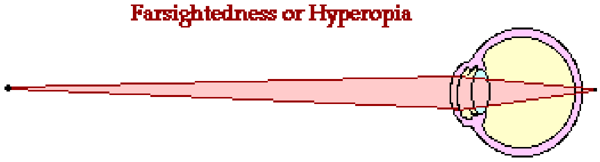
The cornea and lens serve to refract light and focus an image of the object upon the retinal surface.

The ciliary muscles attached to the lens changes the shape of the lens so that the image is always formed on the retina. This change of shape is called accommodation.



Farsightedness or **hyperopia** is the inability of the eye to focus on nearby objects. The farsighted eye has no difficulty viewing distant objects. But the ability to view nearby objects requires a different lens shape - a shape that the farsighted eye is unable to assume. Subsequently, the farsighted eye is unable to focus on nearby objects. The problem most frequently arises during latter stages in life, as a result of the weakening of the ciliary muscles and/or the decreased flexibility of the lens. These two potential causes leads to the result that the lens of the eye can no longer assume the highly convex shape required to view nearby objects. The lens' power to refract light has diminished and the images of nearby objects are focused at a location behind the retina. On the retinal surface, where the light-detecting nerve cells are located, the image is not focused. These nerve cells thus detect a blurry image of nearby objects.

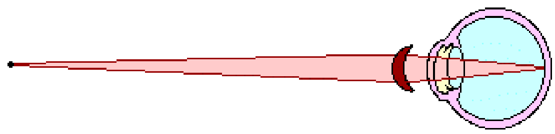
Farsightedness or Hyperopia



The inability of the lens to assume a high curvature and a short focal length leads to the formation of an image located behind the retina.

The cure for the farsighted eye centers around assisting the lens in refracting the light. Since the lens can no longer assume the convex and highly curved shape which is required to view nearby objects, it needs some help. Thus, the farsighted eye is assisted by the use of a converging lens. This converging lens will refract light before it enters the eye and subsequently decreases the image distance. By improving the refracting ability of the eye, the image of nearby objects is once again focused upon the retinal surface.

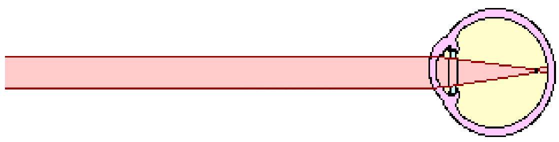
Correction for Farsightedness



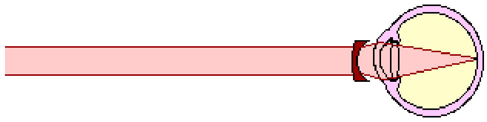
Farsightedness can be corrected by the use of a converging lens. Light refracts before reaching the cornea and is subsequently focused on the retina of the eye.

While farsightedness most often occurs among adults, occasionally younger people will suffer from this vision defect. When farsightedness occurs among youth, the cause is seldom related to the inability of the lens to assume a short focal length. In this case, the problem is more closely related to an eyeball which is shortened. Because the eyeball is shortened, the retina lies closer than

usual to the cornea and lens. As a result, the image of nearby objects is formed beyond the retina. The traditional correction for such a problem is the same as for adults - the use of a converging lens.



A bulging cornea or an elongated eyeball often increases the refracting power of the eye, leading to the formation of images in front of the retina.

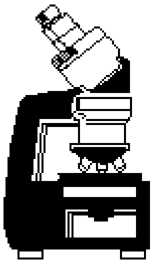


Nearsightedness can be corrected for by the use of a diverging lens. Light diverges before reaching the cornea and is then converged to a location on the retina.

Nearsightedness or **myopia** is the inability of the eye to focus on distant objects. The nearsighted eye has no difficulty viewing nearby objects. But the ability to view distant objects requires that the light be refracted less. Nearsightedness will result if the light from distant objects is refracted more than is necessary. The problem is most common as a youth, and is usually the result of a bulging cornea or an elongated eyeball. If the cornea bulges more than its customary curvature, then it tends to refract light more than usual. This tends to cause the images of distant objects to form at locations in front of the retina. If the eyeball is elongated in the horizontal direction, then the retina is placed at a further distance from the cornea-lens system; subsequently the images of distant objects form in front of the retina. On the retinal surface, where the light-detecting nerve cells are located, the image is not focused. These nerve cells thus detect a blurry image of distant objects.

The cure for the nearsighted eye is to equip it with a diverging lens. Since the nature of the problem of nearsightedness is that the light is focused in front of the retina, a diverging lens will serve to reduce the total refracting power of the eye. The diverging lens acts to diverge light before it reaches the eye; this light will then be converged by the cornea and lens and produce an image on the retina.

Microscopes and Telescopes



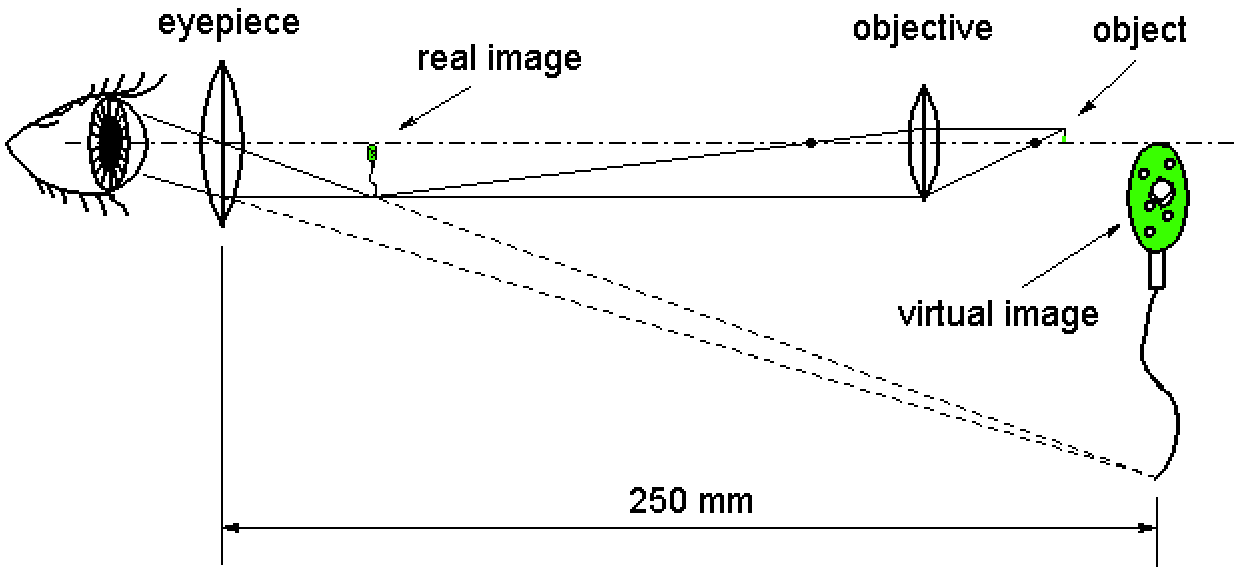


Fig. 7 - Compound microscope (schematic). Notice the likeness to the telescope scheme. What changes is the object distance from the two instruments.

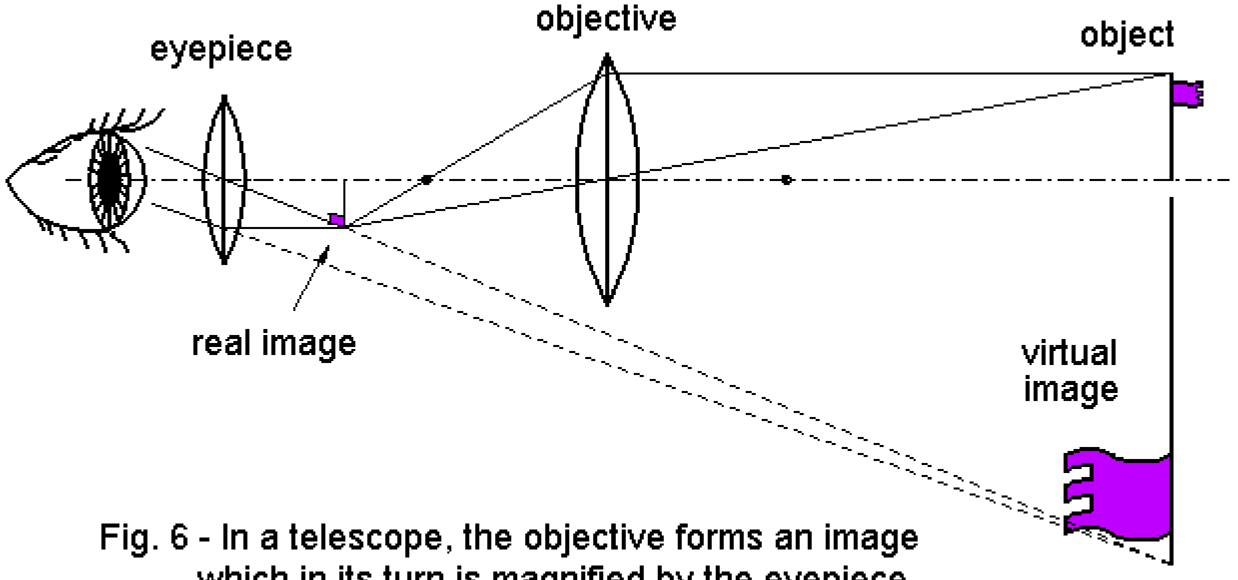
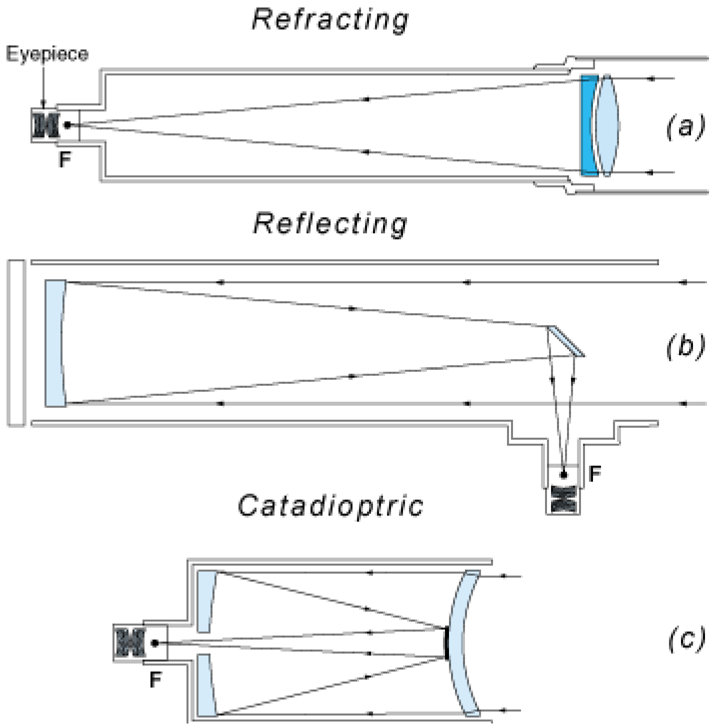


Fig. 6 - In a telescope, the objective forms an image which in its turn is magnified by the eyepiece.

Types of Telescopes

All telescopes fall into one of three optical classes. The relative advantages of each of these telescope designs will be made clear below.

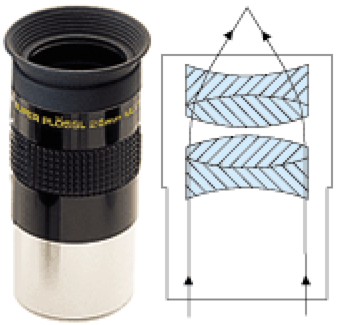


In the refracting telescope (a) light is collected by a 2-element objective lens and brought to a focus at **F**. By contrast the *reflecting telescope* (b) uses a concave mirror for this purpose. The mirror-lens, or catadioptric, telescope (c) employs a combination of both mirrors and lenses, resulting in a shorter, more portable optical tube assembly. All telescopes use an *eyepiece* (located behind the focal point, F) to magnify the image formed by the primary optical system.

Refracting Telescopes use a large objective lens as their primary light-collecting element. Meade refractors, in all models and apertures, include achromatic (2-element) objective lenses, in order to reduce or virtually eliminate the false color (chromatic aberration) that results in the telescopic image when light passes through a lens. Example: Meade Model 230.

Reflecting Telescopes use a concave primary mirror to collect light and form an image. In the Newtonian type of reflector, light is reflected by a small, flat secondary mirror to the side of the main tube for observation of the image. Example: Meade Model 4500.

Mirror-Lens (Catadioptric) Telescopes employ both mirrors and lenses, resulting in optical configurations that achieve remarkable image quality and resolution, while housing the optics in extremely short, highly portable optical tubes. Example: Meade ETX.



Eyepieces of varying focal lengths are used to obtain different powers.

The Eyepiece

With the telescope's primary optics (objective lens, primary mirror, or a combination of lenses and mirrors) having formed an image at the telescope's focus, the purpose of the eyepiece (consisting of two or more small lenses mounted in a metal barrel) is to magnify this image. Eyepieces are available in a wide range of

optical configurations, barrel diameters, and *focal lengths*. It is the focal length of the eyepiece, in conjunction with the focal length of the main telescope, that determines the operating power of the eyepiece. (See How to Calculate Power)

Eyepieces are typically available in focal lengths between 4mm (high-power) and 40mm (low-power). Note that an eyepiece's optical type (MA: Modified Achromatic; PL: Plössl; SP: Super Plössl, etc.) has no effect on power, but does affect such characteristics as the field diameter seen through the telescope, color correction of the image, as well as image sharpness.

A telescope is an amazing device that has the ability to make faraway objects appear much closer! Telescopes come in all shapes and sizes, from a little plastic tube you buy at a toy store for $2, to the Hubble Space Telescope weighing several tons. Amateur telescopes fit somewhere in between, and even though they are not nearly as powerful as the Hubble, they can do some incredible things. For example, a small 6-inch (15 centimeter) scope lets you read the writing on a dime from 150 feet (55 meters) away!

Most of the telescopes you see today come in one of two flavors:

- The refractor telescope, which uses glass lenses.
- The reflector telescope, which uses mirrors instead of the lenses.

Both types accomplish exactly the same thing, but in completely different ways!

To understand how telescopes work, let's ask the following question. Why can't you see an object that is far away? For example, why can't you read the writing on a dime when it is 150 feet (55 meters) away with your naked eyes? The answer to this question is simple: the object does not take up much space on your eye's screen (**retina**). If you want to think about it in digital camera terms, at 150 feet the writing on the dime does not cover enough pixels on your retinal sensor for you to read the writing.

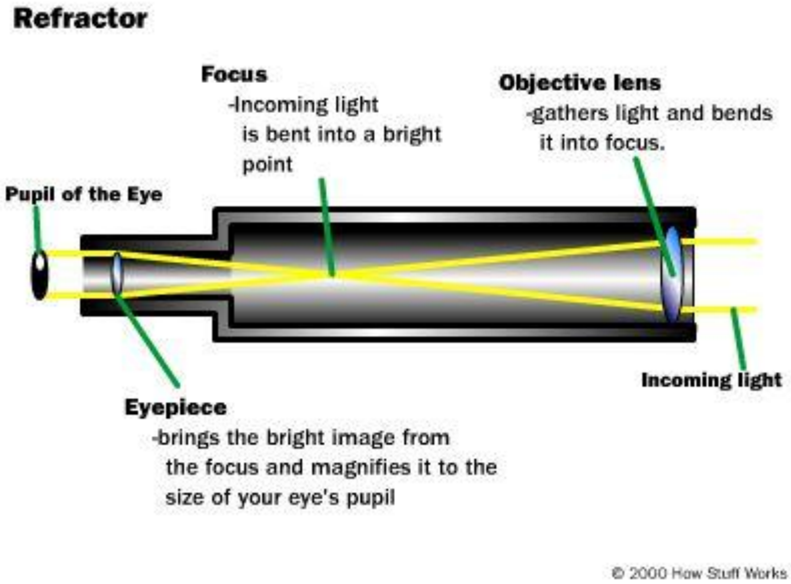
If you had a "bigger eye," you could collect more light from the object and create a brighter image, and then you could magnify part of that image so it stretches out over more pixels on your retina. Two pieces in a telescope make this possible:

- The **objective lens** (in refractors) or **primary mirror** (in reflectors) collects lots of light from a distant object and brings that light, or image, to a point or **focus**.
- An **eyepiece lens** takes the bright light from the focus of the objective lens or primary mirror and "spreads it out" (magnifies it) to take up a large portion of the retina. This is the same principle that a magnifying glass (lens) uses; it takes a small image on the paper and spreads it out over the retina of your eye so that it looks big.

When you combine the objective lens or primary mirror with the eyepiece, you have a telescope. Again, the basic idea is to collect lots of light to form a bright image inside the telescope, and then use something like a magnifying glass to magnify (enlarge) that bright image so that it takes up a lot of space on your retina.

Make a Simple Telescope

1. Get two magnifying glasses (it works best if one is larger than the other) and a sheet of printed paper.
2. Hold one magnifying glass (the bigger one) between you and the paper. The image of the print will look blurry.
3. Place the second magnifying glass between your eye and the first magnifying glass.
4. Move the second glass forward or backward until the print comes into sharp focus. You will notice that the print appears larger and upside down.



This is the simplest telescope design you could have. A big lens gathers the light and directs it to a focal point and a small lens brings the image to your eye.

A telescope has two general properties:

- how well it can collect the light
- how much it can magnify the image

A telescope's ability to collect light is directly related to the diameter of the lens or mirror -- the **aperture** -- that is used to gather light. Generally, the larger the aperture, the more light the telescope collects and brings to focus, and the brighter the final image.

The telescope's **magnification**, its ability to enlarge an image, depends on the combination of lenses used. The eyepiece performs the magnification. Since any magnification can be achieved by almost any telescope by using different eyepieces, aperture is a more important feature than magnification.

To understand how this actually works in a telescope, let's take a look at how a refractor telescope (the kind with lenses) magnifies an image of a distant object to make it appear closer...

Reflectors

Isaac Newton developed the reflector about 1680, in response to the chromatic aberration (rainbow halo) problem that plagued refractors during his time. Instead of using a lens to gather light, Newton used a curved, metal mirror (primary mirror) to collect the light and reflect it to a focus. Mirrors do not have the chromatic aberration problems that lenses do. Newton placed the primary mirror in the back of the tube.

Because the mirror reflected light back into the tube, he had to use a small, flat mirror (secondary mirror) in the focal path of the primary mirror to deflect the image out through the side of the tube, to the eyepiece; otherwise, his head would get in the way of incoming light. Also, you might think that the secondary mirror would block some of the image, but because it is so small compared to the primary mirror, which is gathering a great deal of light, the smaller mirror will not block the image.

In 1722, John Hadley developed a design that used parabolic mirrors, and there were various improvements in mirror-making. The **Newtonian** reflector was a highly successful design, and remains one of the most popular telescope designs in use today.

Binoculars

Some optical instruments, such as periscopes and binoculars use trigonal prisms instead of mirrors to reflect light around corners. Light typically enters perpendicular to the face of the prism, undergoes TIR off the opposite face and then exits out the third face. Why do you suppose the manufacturer prefers the use of prisms instead of mirrors?